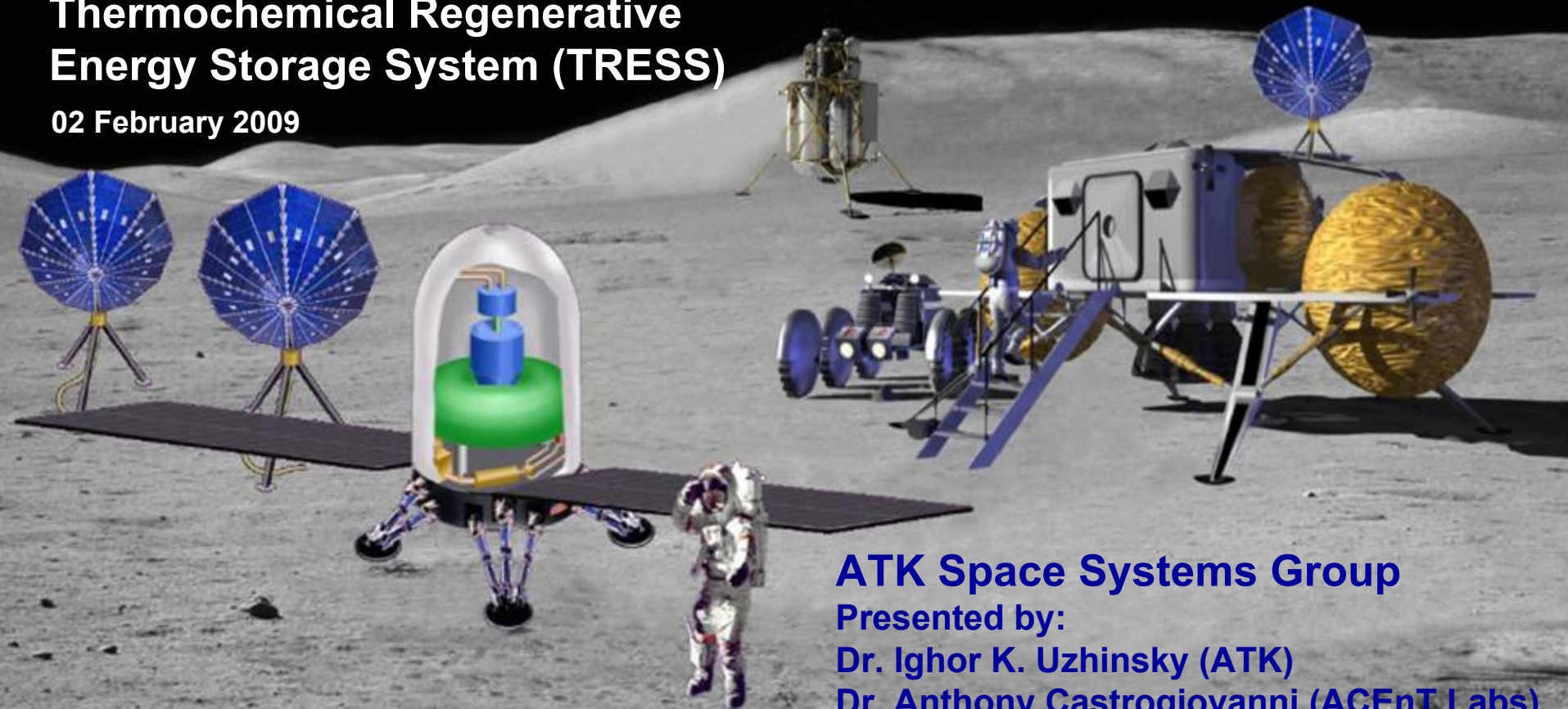


NASA Lunar Surface System Study

Topic 4: Long-term Lunar Energy Storage Systems Concepts

ATK Final Review (NNJ08TA80C) Thermochemical Regenerative Energy Storage System (TRESS)

02 February 2009



ATK Space Systems Group

Presented by:

Dr. Ighor K. Uzhinsky (ATK)

Dr. Anthony Castrogiovanni (ACEnT Labs)

- **Presentation Objectives**
- **Study Program Plan Review**
- **Comments from Mid Term Review**
- **Brief TRESS Concept Review**
- **System Architectures (stationary and mobile)**
- **Key Subsystem Updates**
- **Integrated Risk Summary**
- **System Figure-of-Merit Sensitivity Analysis Results**
- **Technology Applications**
- **Technology Development Plans**
- **Summary and Q&A**

- **Review of NNJ008TA80C contract requirements**
- **ATK TRESS team**
- **Review TRESS concept as a reminder of CONOPS**
- **Update subsystem investigations since mid term review**
- **Present system configurations**
- **Present integrated risk summary updated with latest info**
- **Present quantitative results of Figure-of-Merit sensitivity analyses**
- **Discuss other applications of underlying technologies and variations of TRESS**
- **Discuss proposed plans for development to TRL 6**

Within the scope of NNJ08TA80C, ATK Space Systems was contracted to undertake:

- **A conceptual design study of the integration and performance of the Thermochemical Regenerative Energy Storage and generation System (TRESS) utilizing magnesium hydride (MgH_2) and a hydrogen peroxide (H_2O_2) solution as energy carriers.**
- **The size for each subsystem is to be determined for efficient integrated operation, including supply of the solid materials to the system's reactors, and required inputs (power and materials) and calculated outputs for each subsystem will be determined.**
- **The estimated mass and size of each subsystem is to be provided, and any special considerations in terms of fragility, packaging, and handling for space launch and lunar delivery will be identified.**
- **Each of the TRESS subsystems is to be analyzed and evaluated in terms of its performance, operational life, reliability, service and maintenance requirements, monitoring of subsystem operations, operating in the lunar environment, potential for technical upgrades, current Technology Readiness Level (TRL) status and anticipated progress, and the subsystem specific issues.**

- **Interim Study Report due on November 10, 2008: 1 Hard Copy and 1 CD-ROM**
- **Interim Oral Presentation November 17, 2008**
- **Final Study Report due February 9, 2009: 1 Hard Copy and 1 CD-ROM**
- **Collaborative Technical Exchange with Awardees and broader community due February 24-26, 2009: 3 days in duration**

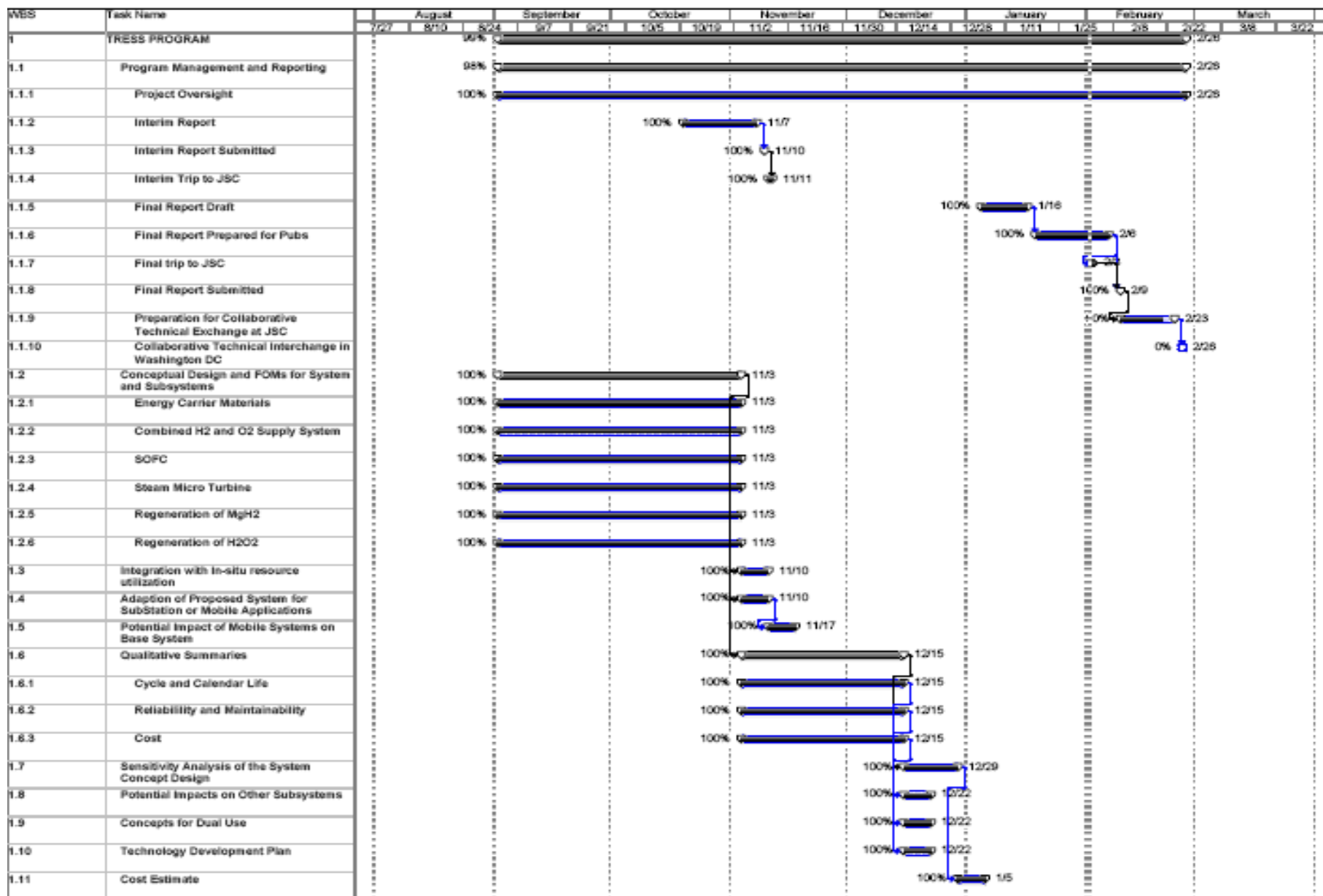
The following WBS items have been completed and the results and considerations will be addressed in the final ATK Space Systems NNJ08TA80C contract report.

- Energy Carrier Materials
- Combined Hydrogen and Oxygen Supply System (CHOSS)
- Solid Oxide Fuel Cell (SOFC)
- Steam Micro Turbine
- Regeneration of MgH_2
- Regeneration of H_2O_2
- Integration with In-Situ Resource Utilization
- Adaption of proposed system for substation or mobile applications
- Potential impact of mobile systems on base system
- Sensitivity analysis of the system concept design
- Potential impacts on other subsystems
- Concepts for dual use
- Technology development plan
- Qualitative summaries

NNJ008TA80C Program Schedule



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Program Manager – Dr. Ighor Uzhinsky

Principal Engineer and Scientist – Dr. Tony Castrogiovanni

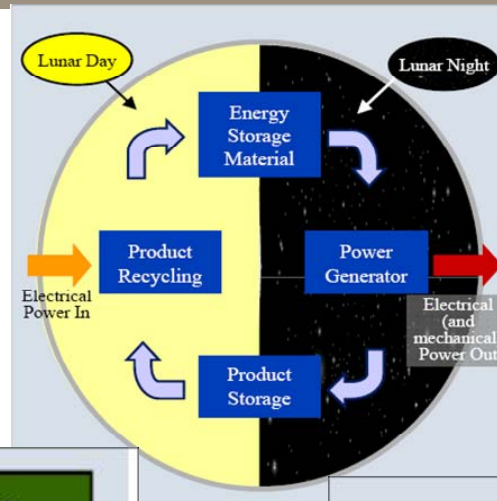
- Led engineering of all TRESS subsystems, system-level analysis and balance of plant/energy management
- Developed system performance evaluation models, conducted trade-off analysis of the system and sub-systems, led and coordinated 3-D modeling efforts and implementation concepts for TRESS and related technologies

Key Subsystem Principal Investigators:

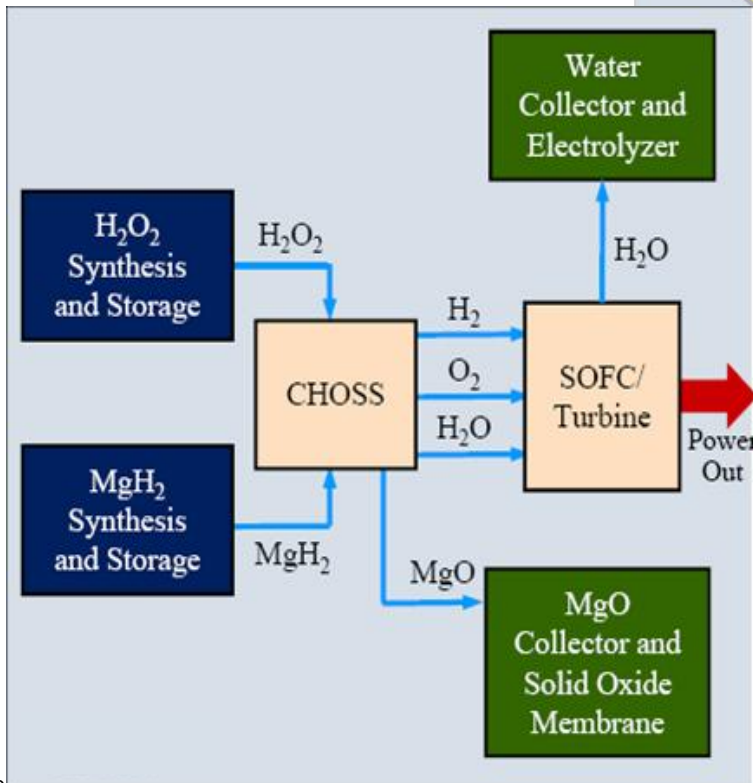
- **CHOSS and Engineering Design – Florin Girlea, Joe Alifano**
 - Provided CHOSS engineering design data, 3-D models of the system components and of the system.
- **SOFC, Turbine and MgO recycling – Chris Kogstrom**
 - Developed concept of operations, performance data, evaluated current and future technological status and design of SOFC technology
 - Led the development, evaluation and conceptual design for SOM MgH₂ recycling process. Led cooperative analysis and investigation of SOFC and SOM technologies with Boston University and Accumetrics
- **H₂O₂ storage and synthesis – Dr. Akiva Sklar**
 - Provided design criteria, operational requirements, participated in analysis and design of process flows, mass/volume/energy/ safety/performance and other essential features of the H₂O₂ recycling system
 - Led cooperative efforts with Headwaters Technology Innovations for the development of the system and major components detailed design and evaluation

- Consider synergies including
 - Mobile systems and distribution to remote locations
 - Solar concentrator heat from regolith processing
 - ISRU
 - Molten salt processes for regolith processing (metals)
 - Emergency life support (O_2 and water)
 - Reactants as rocket propellants
- Assess concern over powder handling and identification of any potential “show stopper” issues
 - e.g. contamination and system fouling
- Address impact of launch and transport environment
 - e.g. shock and vibration on ceramics etc.

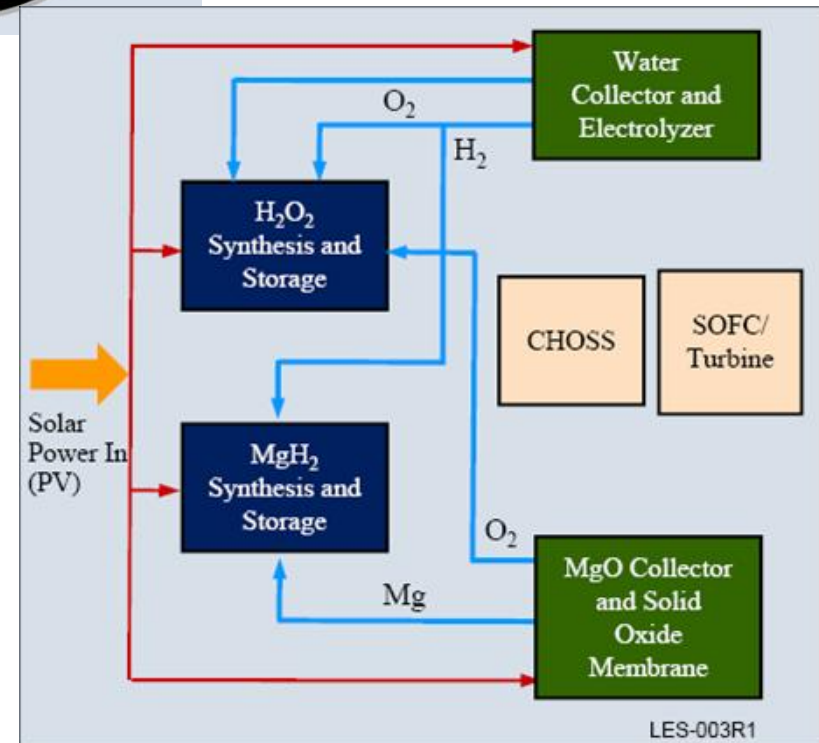
TRESS Night and Day Cycles



Night – Power Out

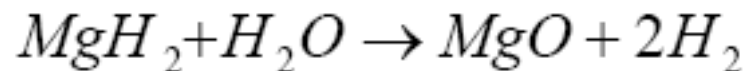
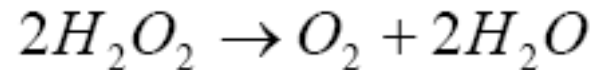
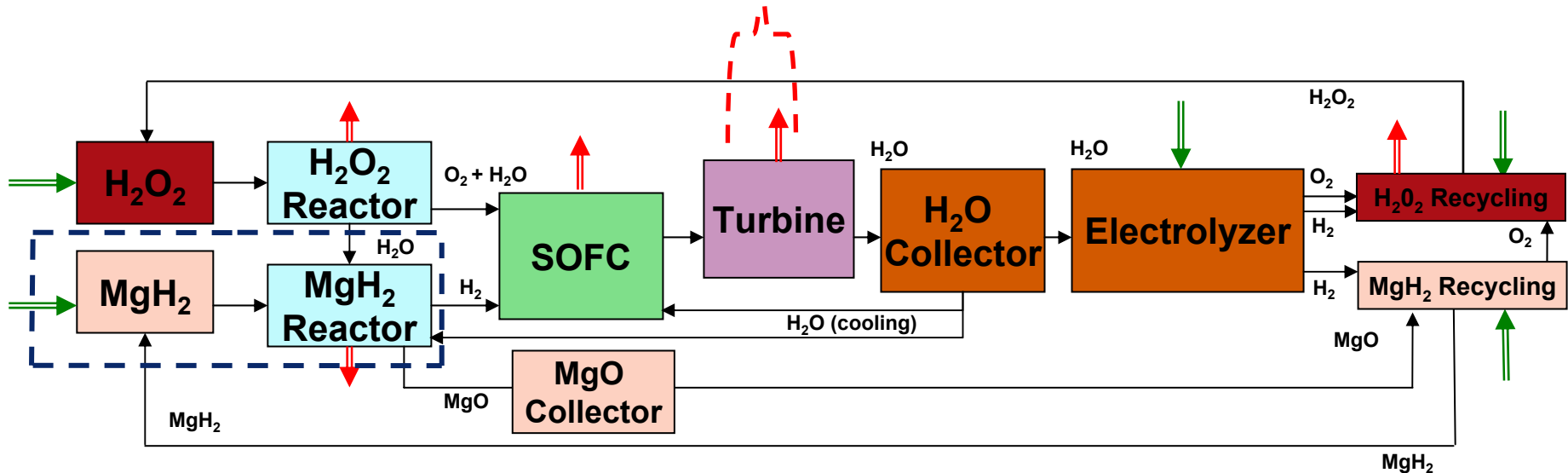


Day – Power In



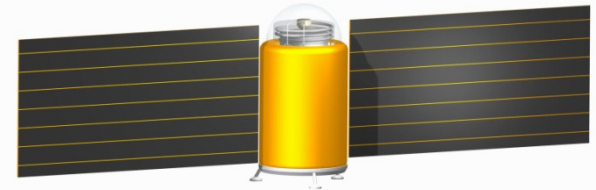
LES-003R1

Fundamental TRESS Cycle



The basic concept centers around the efficient storage of energy in hydrogen peroxide and magnesium hydride

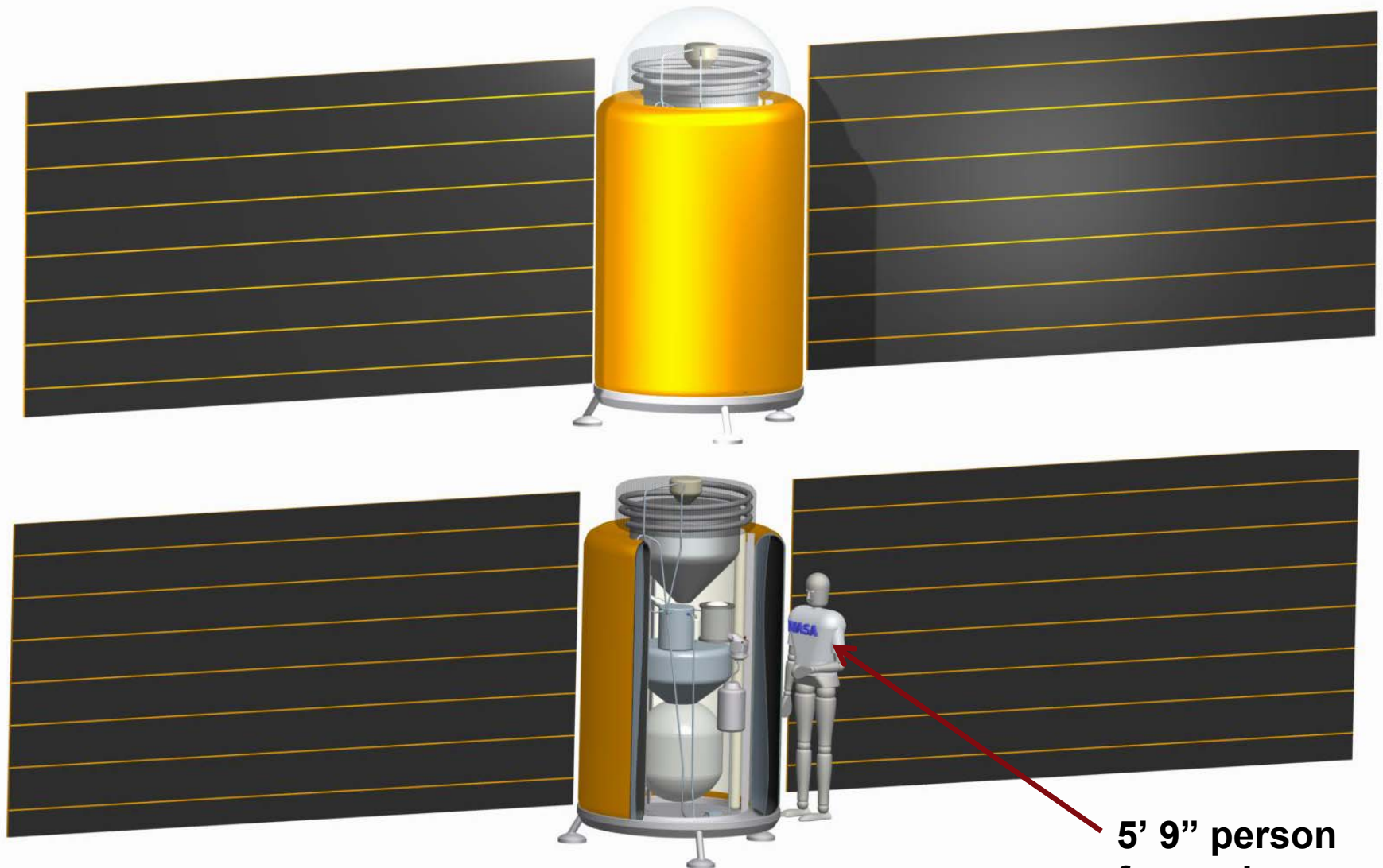
- Pod configuration
- Sealed from lunar environment in dome (radiation shield)
- Readily deployable from lander
- Electrical interfaces
 - Power in from PV array
 - Power out
- Mass \approx 2,000 kg



TRESS Pod with Heat Rejection Arrays



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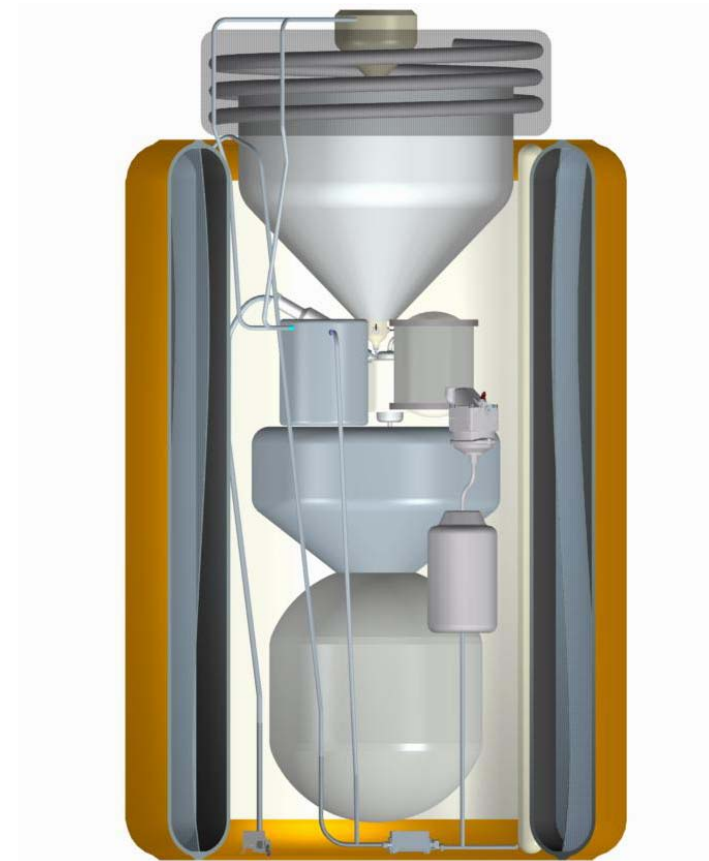
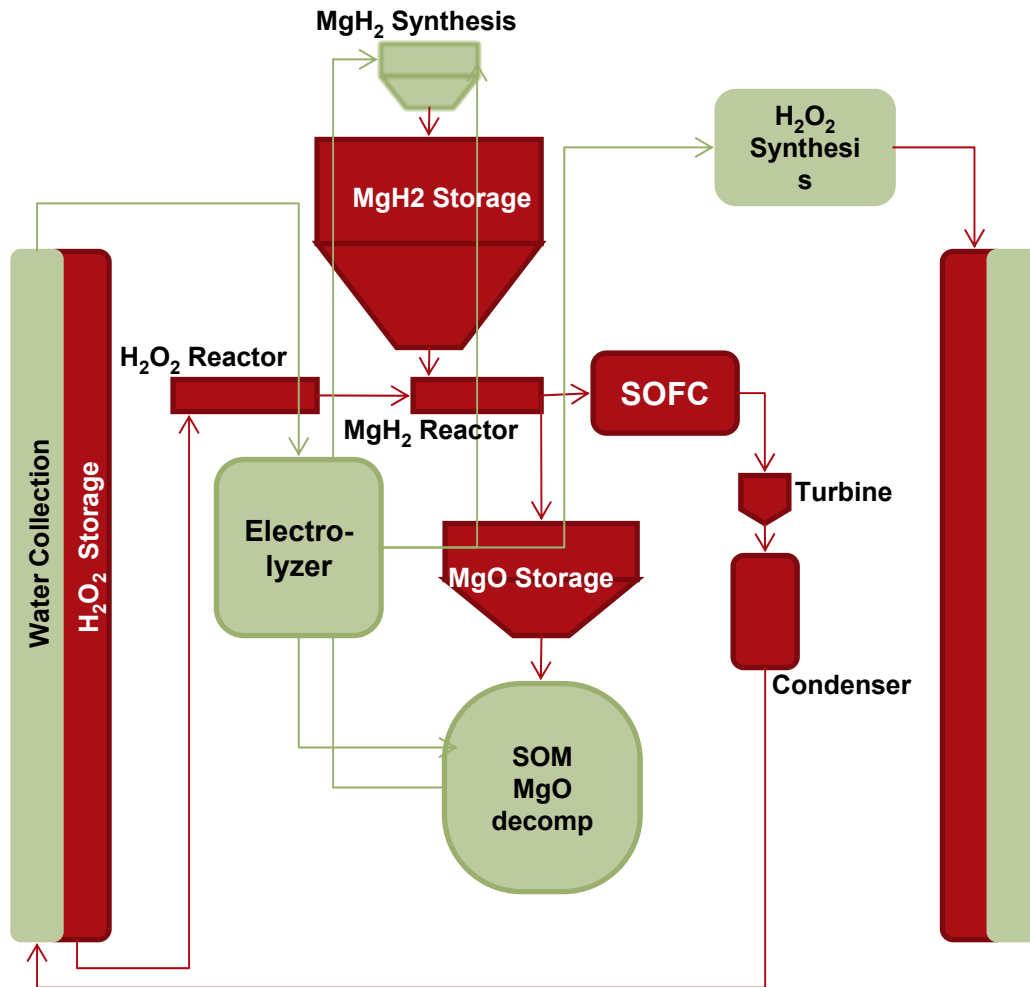
5kW, 2000 kWh System Depicted

**5' 9" person
for scale**

TRESS System and Components Design Status

Concept of Operation

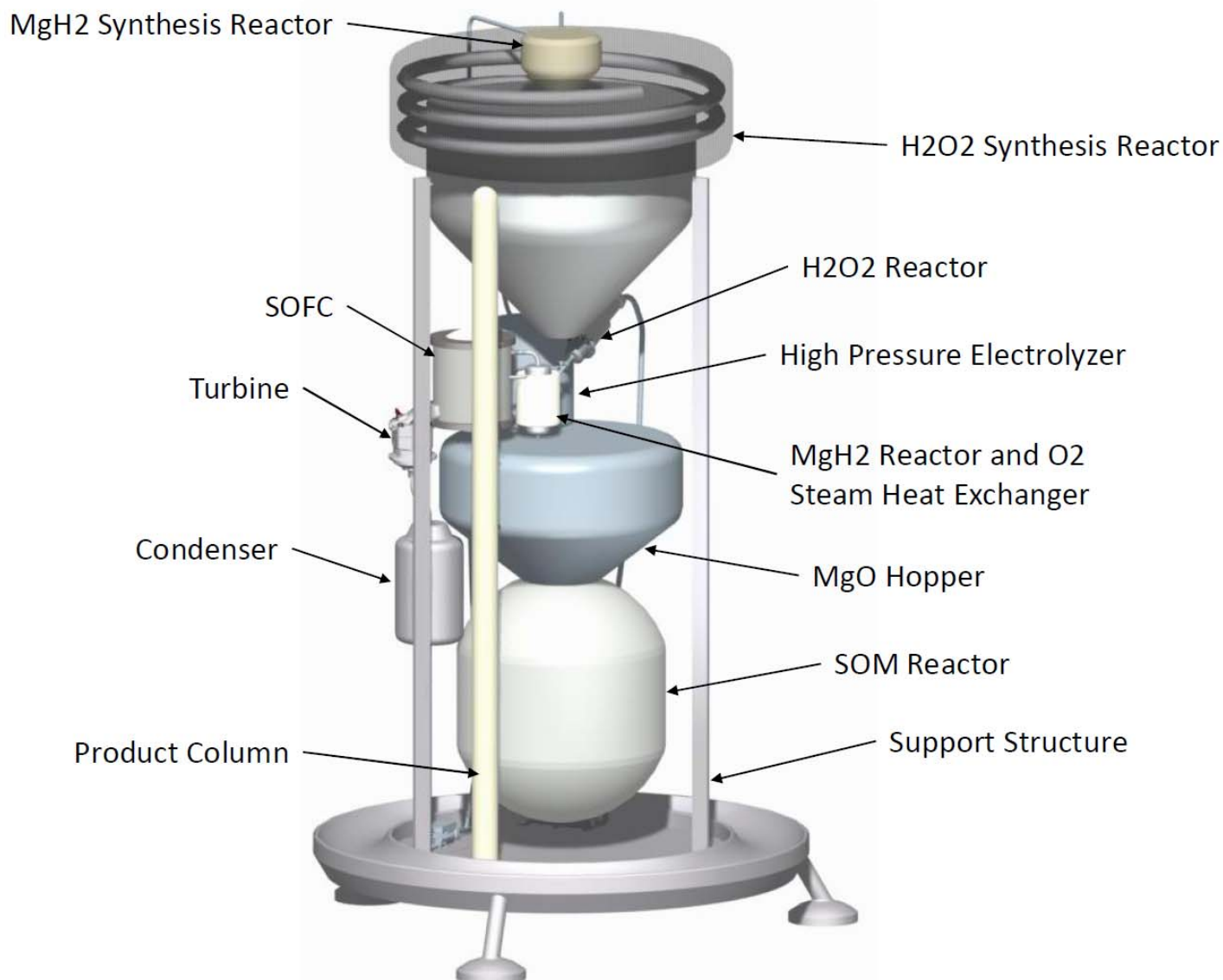
System Block Diagram with Orientation



TRESS System Isometric (Peroxide Tank Removed)



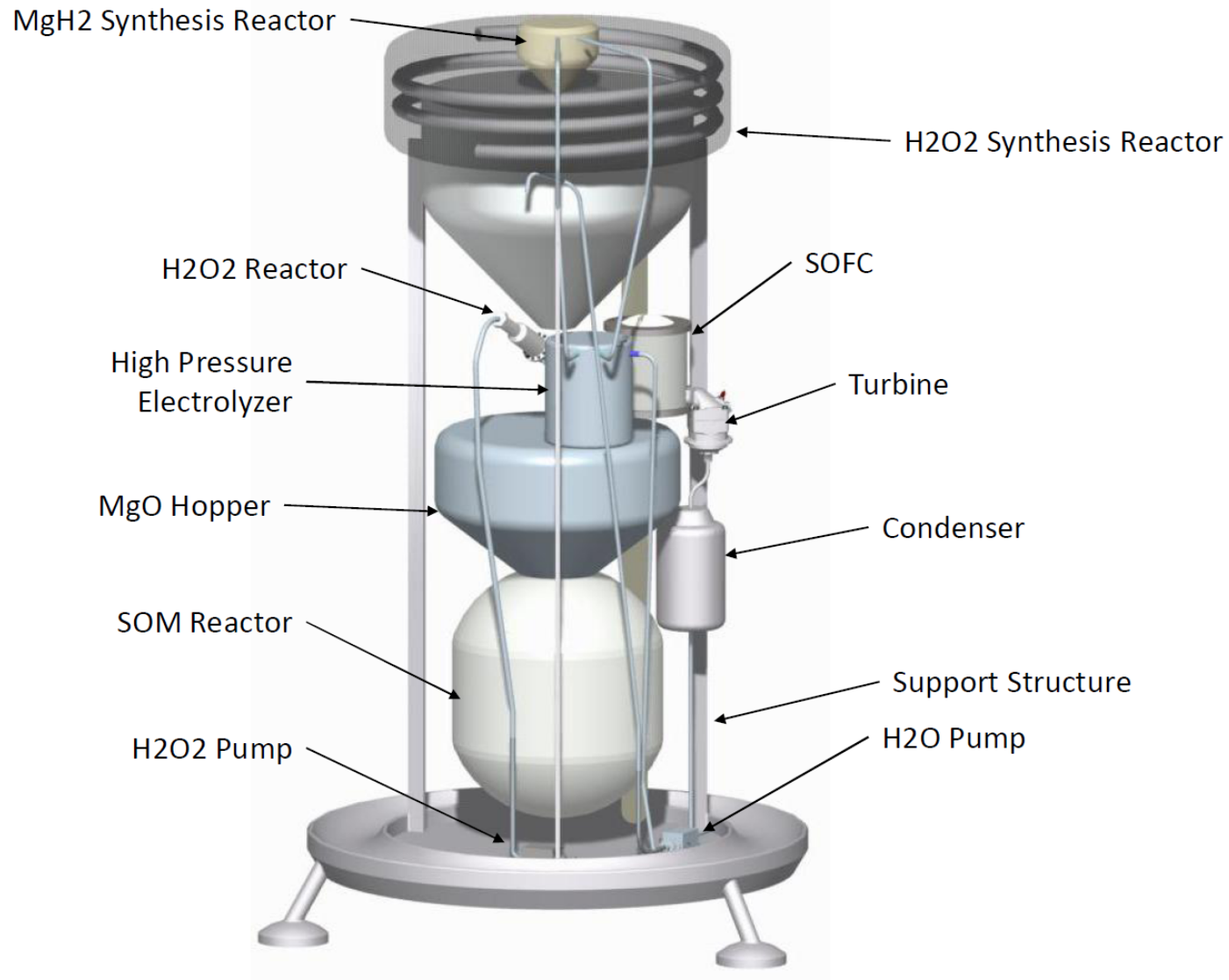
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TRESS System Isometric (Peroxide Tank Removed)

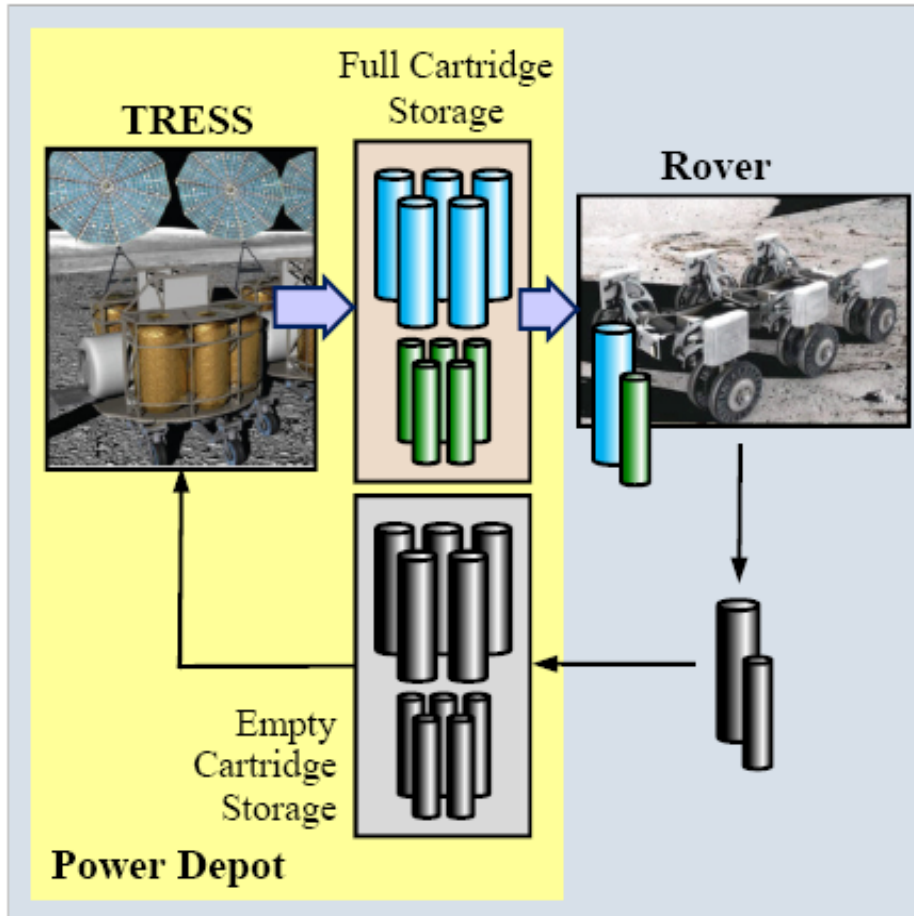


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TRESS Mobile (Rover/Remote Outposts) Applications **ATK**

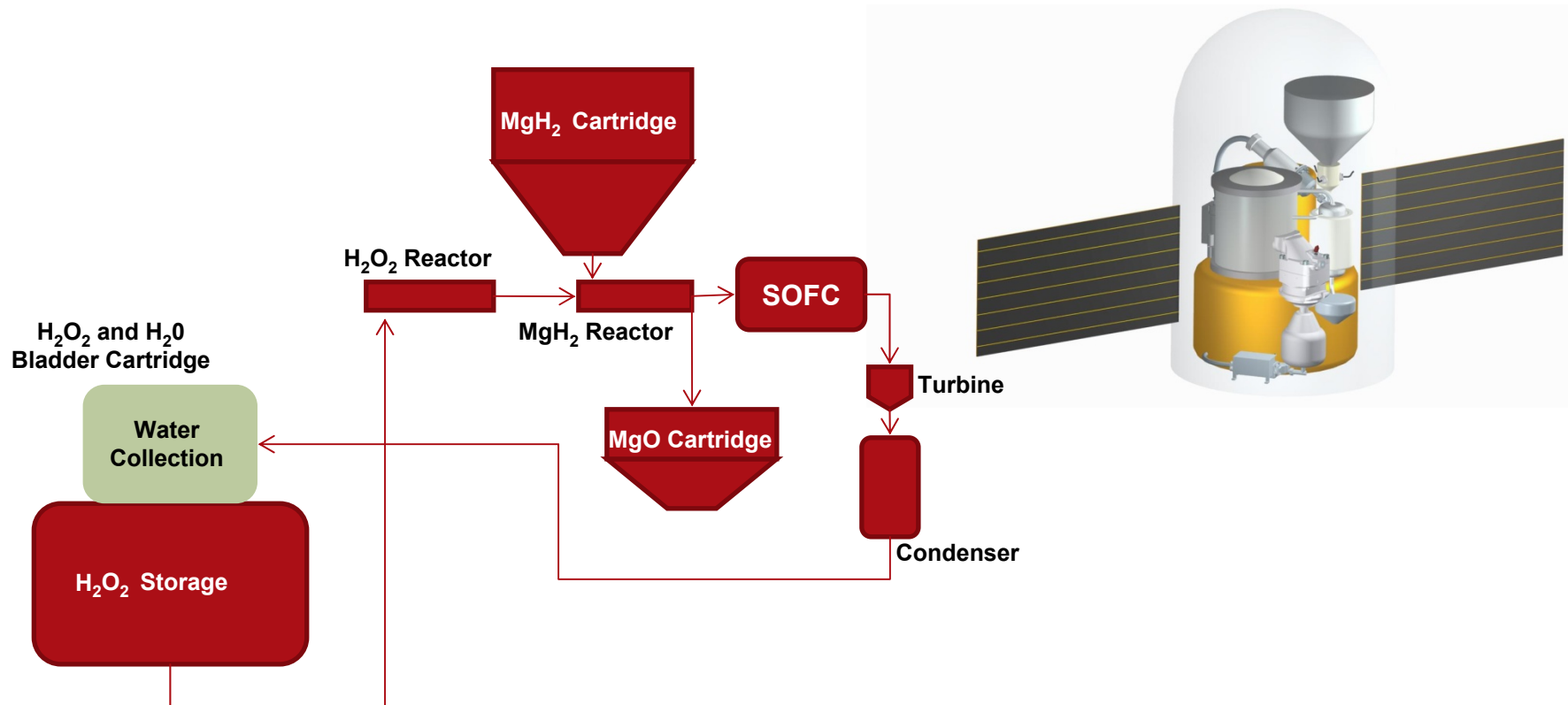
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- Mobile units use encapsulated MgH_2 powder and peroxide cartridges that can be easily exchanged from a central depot or remote supply caches
- No need for on-board recharging
- Modular power cartridges may be distributed to any place on the lunar surface where common power generator interfaces are provided
- The cartridges are safe for long-term storage and may be delivered to the areas of interest in advance of particular missions.

Mobile TRESS Block Diagram with Orientation

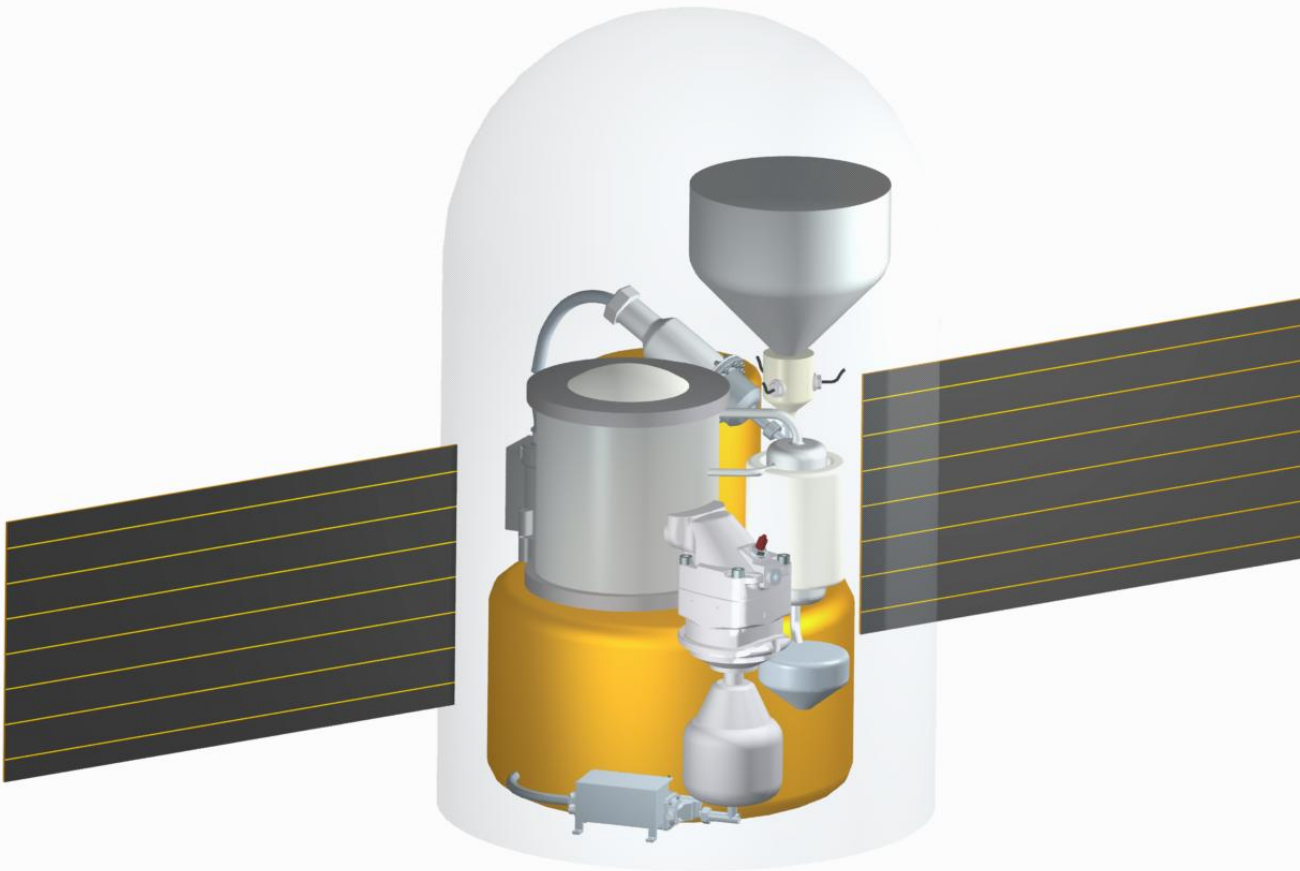
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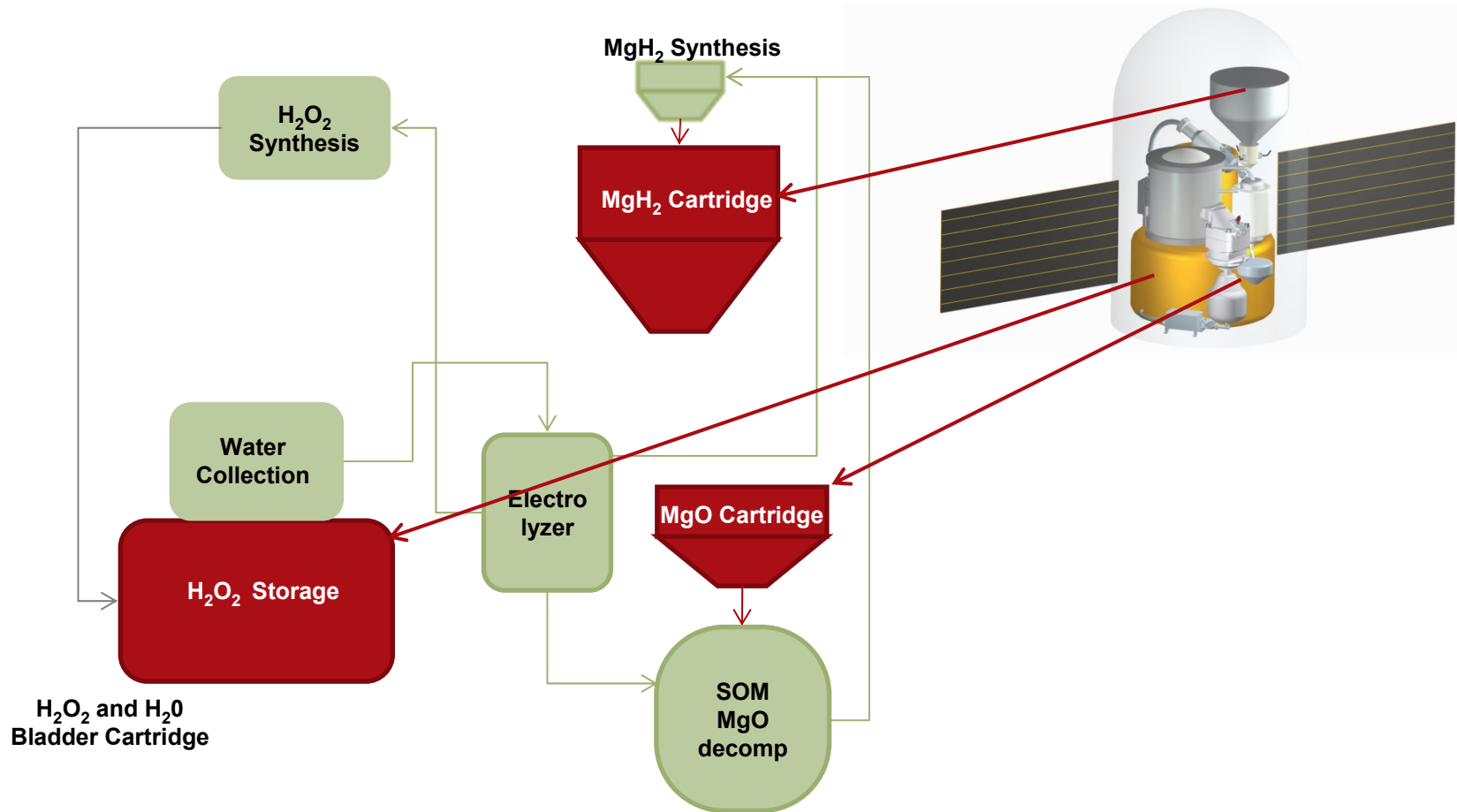
**Only TRESS Power Generation Components
Required for Mobile Applications**

System is ~18" Φ x 32" H + heat rejection panels

Mass \approx 80kg (0.5 kWh/kg)



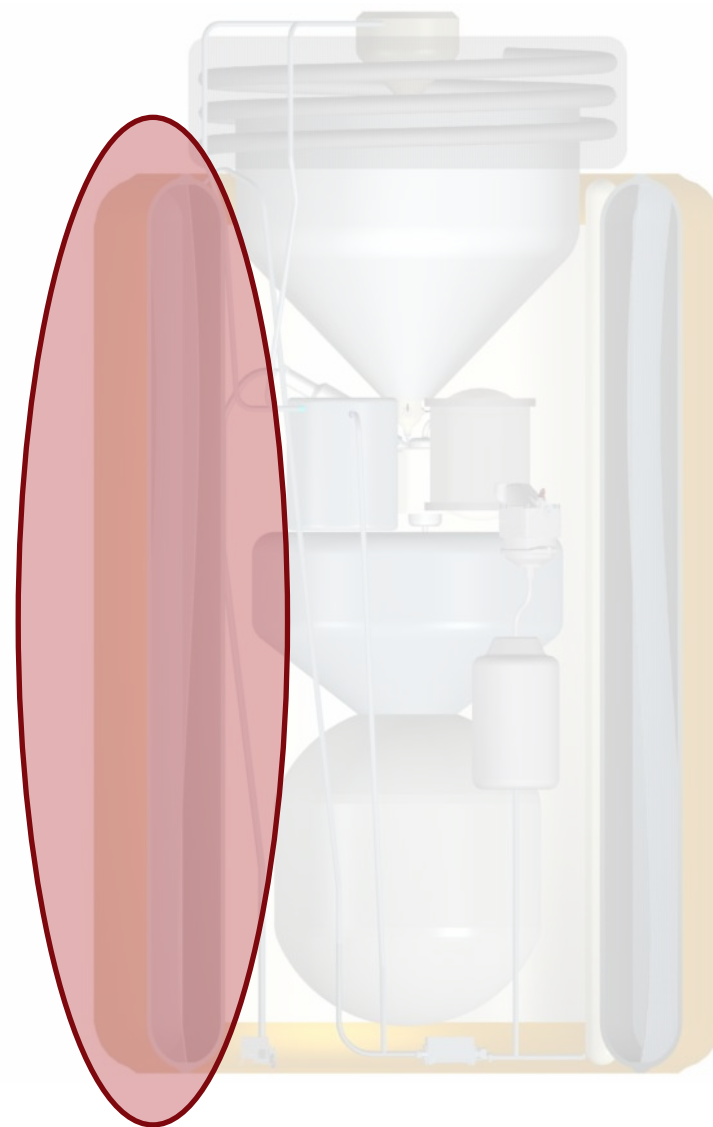
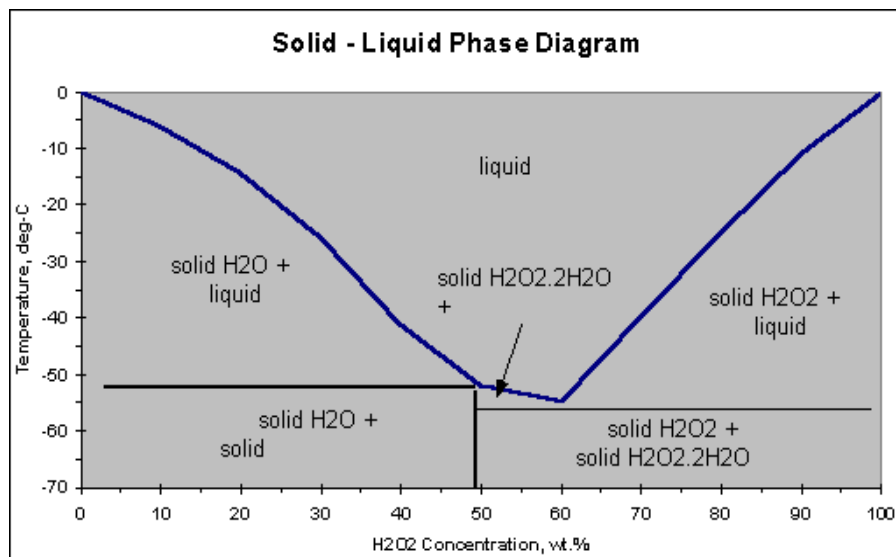
Regeneration Station for Mobile System



**Mobile Cartridges are Inserted into
Regeneration Pod**

SUBSYSTEM UPDATES

- **Toroid-Cylinder with Bladder**
- **$\text{H}_2\text{O}_2 + \text{H}_2\text{O}$ on inside, H_2O Collection on Outside**
- **Largest Volume Component**
- **Key issue = compatibility with HBr and HCl (from synthesis reactor) and thermal management**



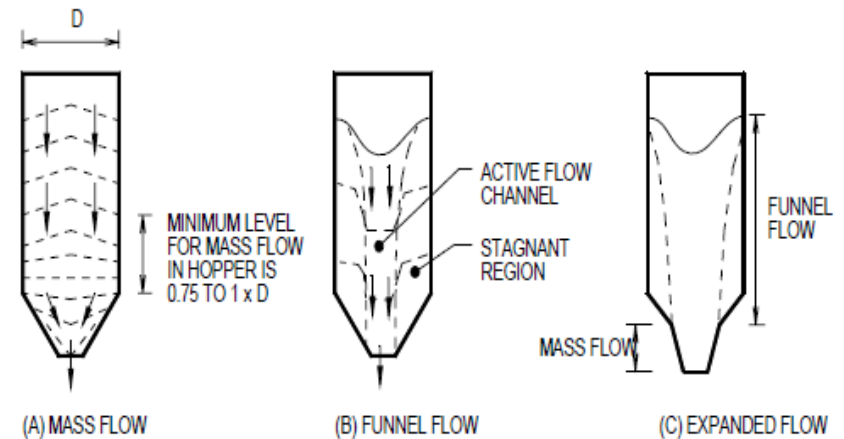
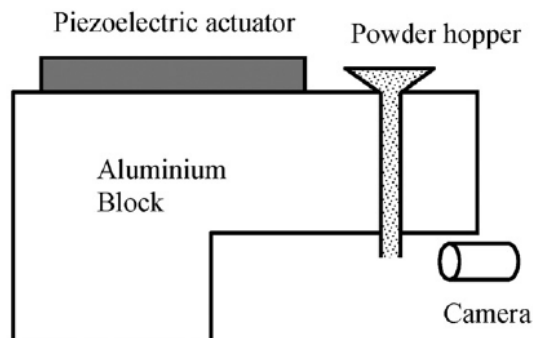
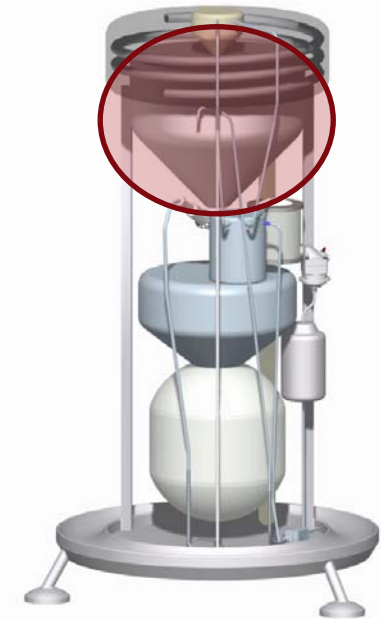
Aqueous Peroxide Storage – Risk Summary



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Risk Items	Effect(s)	Importance/ Likely-hood	Technical Risk	Mitigation Measures
Safe and uniform thawing of frozen hydrogen peroxide + water mixture	Safety and operating issues, non-uniform melting results in incorrect stoichiometry and thermal balance for system	High	Med	Thermal analysis of configuration, engineering of heat exchanger system to provide for uniform melting
Corrosion due to residual HBr and HCl additives from synthesis process	Reduced life of vessel material and bladder material	Med	Low	Select materials with excellent compatibility with H_2O_2 , and dilute HBr and HCl. Test for verification
Leakage due to thermal cycling of tank in lunar environment	Leakage results in loss of reactants and potential contamination of contents with lunar regolith	Med	Med	Reduce seal areas (i.e. use fully welded construction). Careful thermal analysis of system

- Dry Powder hopper
- Ultrasonic micro-dispenser
- Vibration-assisted flow
- Key issues – low gravity and dispense to pressurized reactor



The Johanson equation for mass flow (W)

$$W = \rho_b (\pi/4) B^2 (g B/4 \tan \theta_c)^{0.5}$$

The Beverloo equation :

$$W = 0.58 \rho_b g^{0.5} (B - kd_p)^{2.5}$$

In these equations:

ρ_b is the bulk density (kg/m³)

g is the gravitational constant

B is the outlet size (m)

k is a constant (typically 1.4)

d_p is the particle size (m)

The key result is that powder flow is proportional to the square root of gravity, suggesting that a mass flow ratio may be predicted as follows:

$$\frac{W_{lunar}}{W_{earth}} = \left(\frac{1.622 \text{ m/s}^2}{9.806 \text{ m/s}^2} \right)^{1/2} = 0.407$$

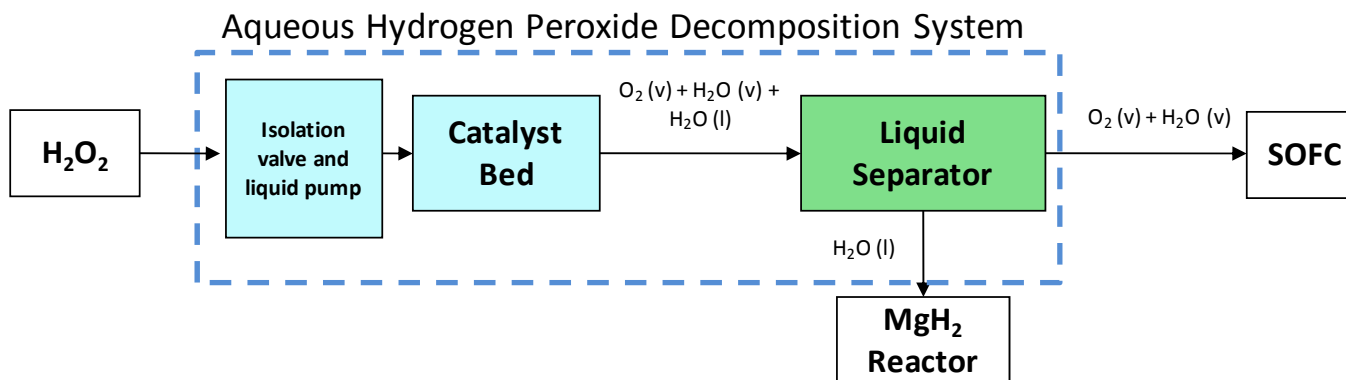
MgH₂ Storage – Risk Summary



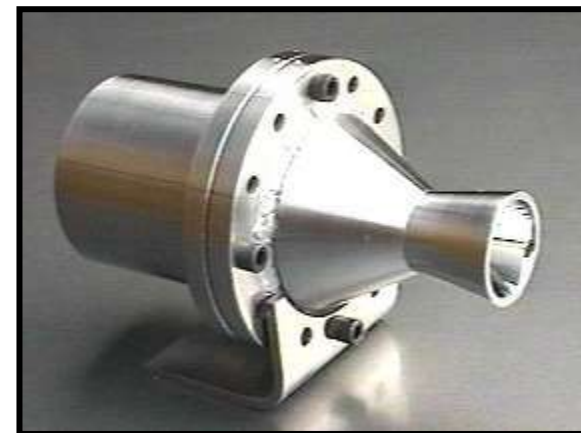
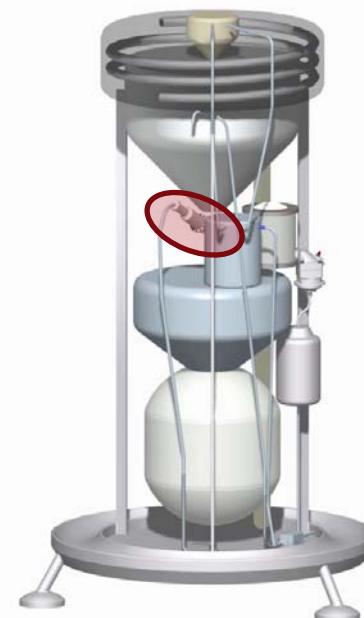
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Risk Items	Effect(s)	Importance / Likely-hood	Technical Risk	Mitigation Measures
Accurate control of powder dispense in reduced gravity and low temperature	Non-uniform dispensing results in incorrect stoichiometry and thermal balance for system	High	Med	Leverage experience from pharmaceutical industry. Carefully calibrate system
Lack of complete expulsion of powder due to stagnant regions in hopper	Inefficient use of volume – reduction in energy storage capacity	Med	Low	Proper design of hopper and inclusion of vibration or other acoustic means to mitigate powder agglomeration
Backflow of steam due to powder dispense to pressurized reactor	Reaction in powder hopper	High	High	Backpressure hopper to above steam pressure (not desired). Supersonic injection (ejector) similar to HVOF flame spray.

Peroxide Decomposition System

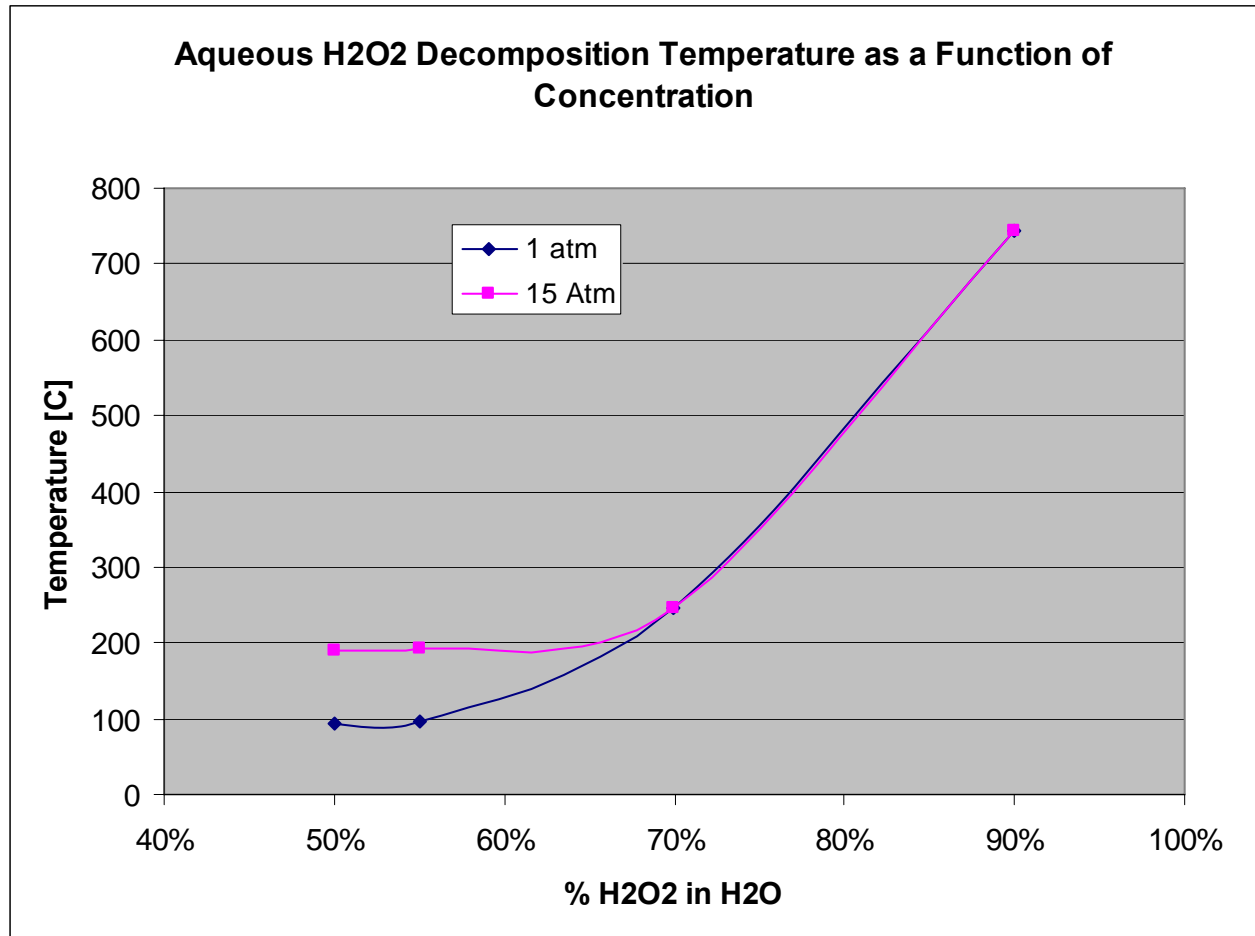


- **Passive transition metal catalyst bed similar to peroxide monopropellant rockets**
- **Exothermic decomposition reaction**
- **At < 67% concentrations, temperature is limited to saturation at set pressure**
- **Product (<67%) is O₂ and high quality steam**
- **Gravity-based liquid/water separator**



Peroxide Concentration Plays a Key Role

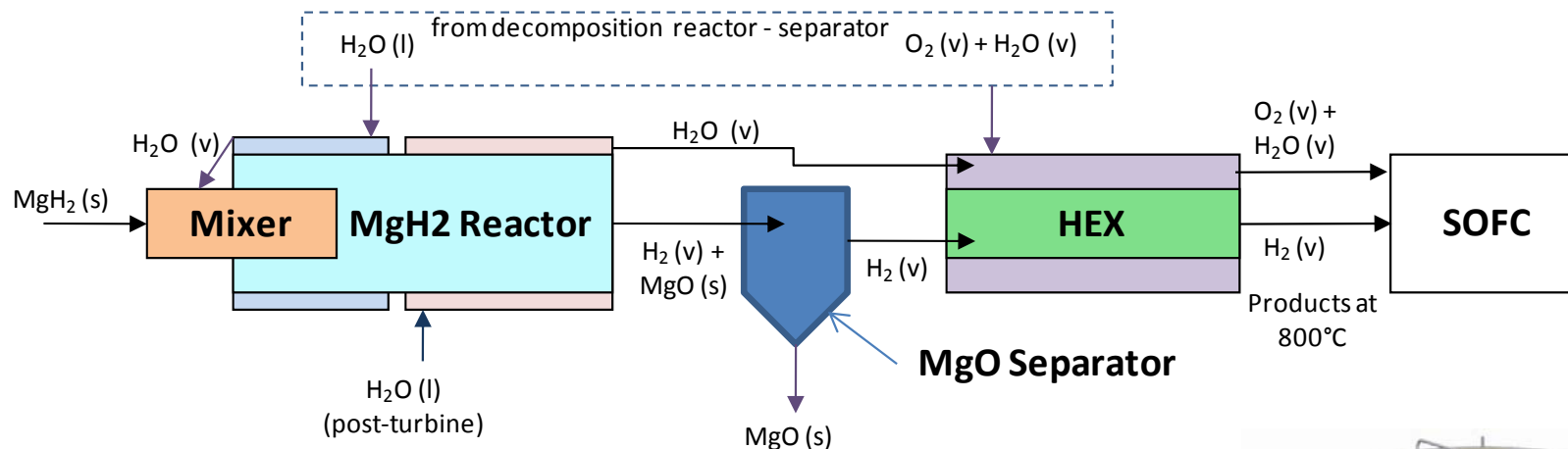
- 15atm systems operating with 55% and 75% concentrations considered
- Dilution with post-turbine water for concentrations > 67%



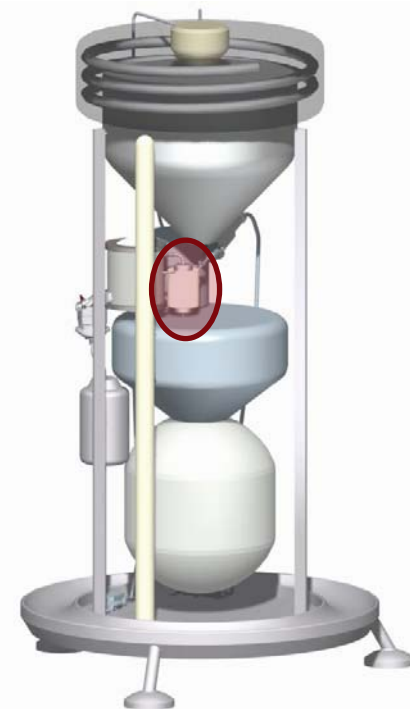
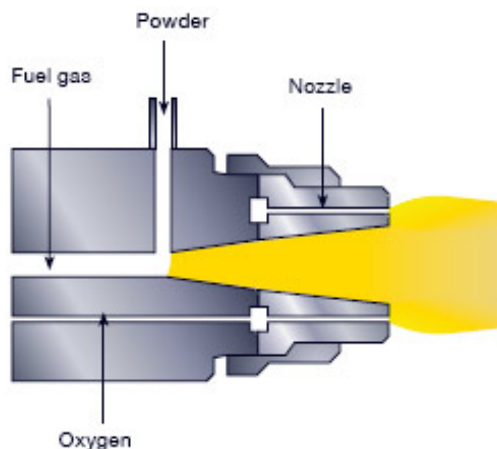
Peroxide Decomposition System – Risk Summary

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Risk Items	Effect(s)	Importance/ Likely-hood	Technical Risk	Mitigation Measures
Incomplete decomposition of H_2O_2	Incorrect stoichiometry and thermal/energy balance for system	High	Low	Insure adequate residence time in catalytic reactor. Test and verify.
Contamination of H_2O_2 with trace quantities of HBr and HCl from synthesis process	Corrosion of catalyst and reduced life of subsystem.	High	Med	Experimental verification of material life with trace quantities of the additives
Inefficient separation of liquid water from steam/oxygen mixture. Possible impact of reduced gravity	Potential for O_2 in MgH_2 reactor or incorrect flow rate of water resulting in potential for thermal imbalance	Med	Low	Experimental verification of gravity-based separation scheme. Analytical assessment of reduced gravity effects.



- Based on powder/flame spray gun technology
- Key is mixing efficiency and residence time to complete reaction



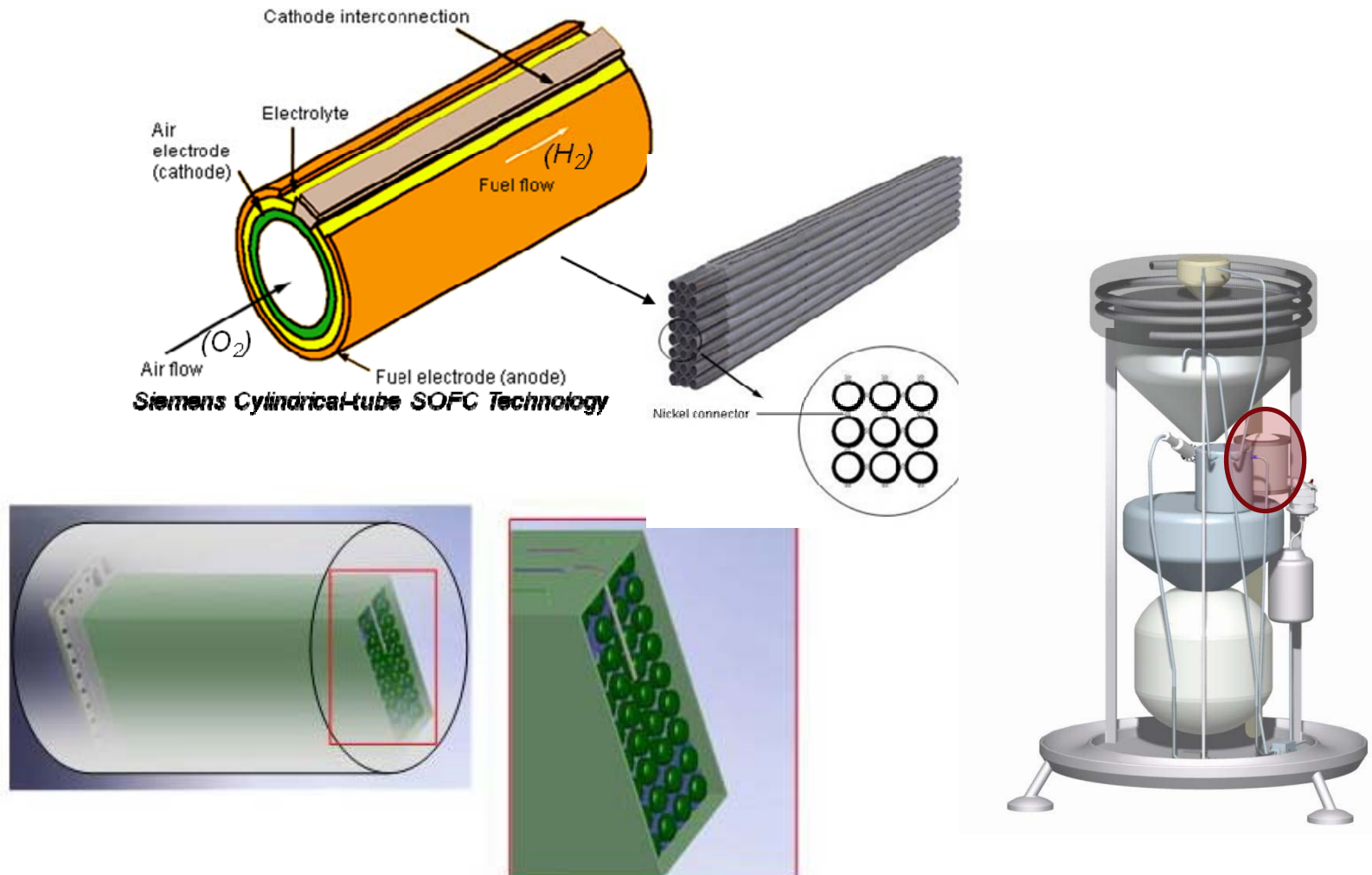
Magnesium Hydride Reactor – Risk Summary



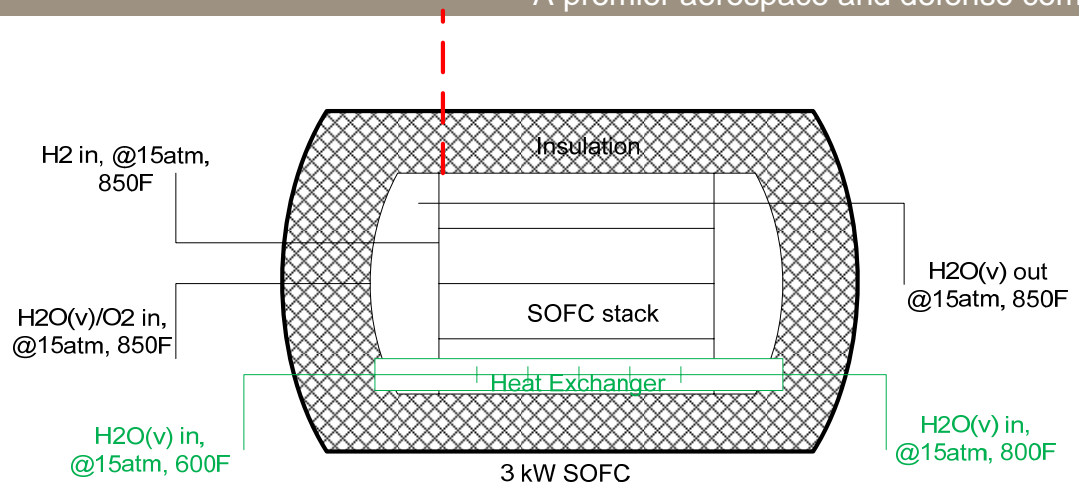
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Risk Items	Effect(s)	Importance/ Likely-hood	Technical Risk	Mitigation Measures
Inefficient mixing of powder and steam	Incorrect stoichiometry results in low H ₂ yield and undesired products (e.g. Mg, Mg(OH) ₂)	High	High	Extensive design and test of system. Leverage experience from flame spray industry
Inefficient heat exchanger performance or coolant flow distribution + transients	Thermal imbalance to system – can reduce life of SOFC due to thermal distortion	High	Med	Detailed thermal and fluid system analysis. Extensive testing. Review sources of initial heating to insure system can “start”. Assess application of small electric heater.
HBr + HCl contaminants	Potential creation of unwanted compounds MgCl ₂ and MgBr ₂	High	High	Assess with bench-scale tests
Inefficient separation of MgO from H ₂	Particulates will accumulate on SOFC anode	High	Med	Testing of alternative particle separators, backup filter
H ₂ in MgO collector headspace	H ₂ in SOM process. Small loss of H ₂ per cycle (0.01 kg)	Low	Med	Keep MgO headspace volume low. Vent MgO vessel prior to SOM regeneration

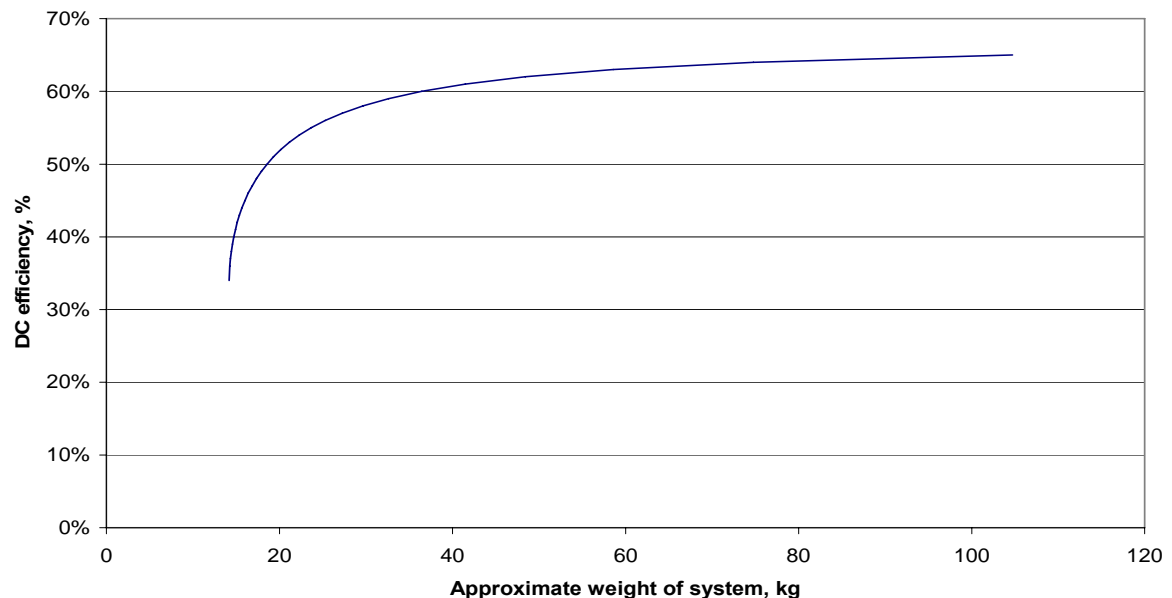
- Accumetrics Cylindrical Configuration is Baseline



- **Additional cooling required to maintain proper operating temperature**
- **Systems normally operate with 2x excess air to provide heat sink**
- **High efficiency possible with sacrifice of weight**



Comparison of the Theoretical Weight and Efficiency of an Acumentrics Fuel Cell Running on Hydrogen and Oxygen at 15atm and at 3000WDC



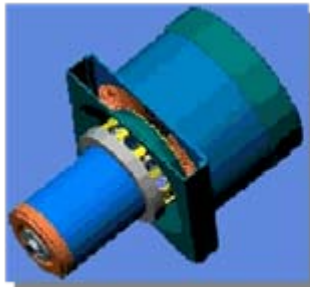
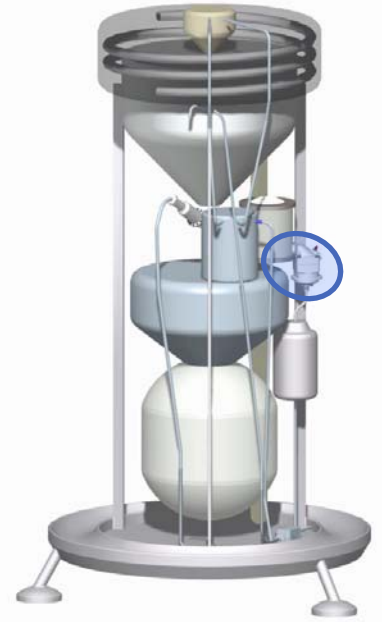
Risk Items	Effect(s)	Importance/ Likely-hood	Technical Risk	Mitigation Measures
YSZ Membrane Material Degradation due to contamination	Reduced efficiency, life, maintenance	High	Med	Evaluate durability and damage tolerance through testing in relevant conditions. Based on results consider alternative architectures and materials.
High pressure and thermal management particular to TRESS	System efficiency, weight, life	Med	Med	Design/test with H ₂ O cooling . Evaluate shock resistance and subsystem contaminant effects with high power density low weight designs. Reduce power density to achieve system reliability goals.
Poor operability in off peak conditions	Efficiency	Med	Low	Review the expected operation range and consider design changes.

Nighttime Waste Heat Recovery - Micro Turbine



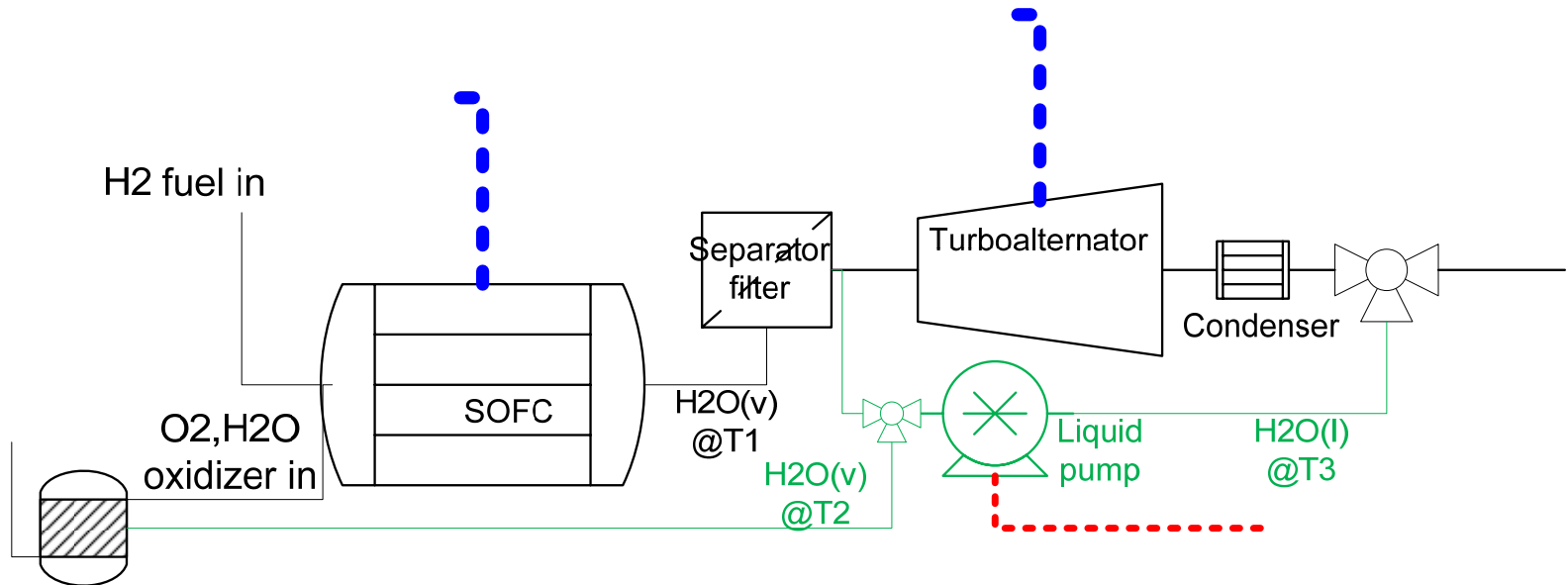
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- Microturbine has highest power to weight
- We need $P_{in}/P_{out} = 270$ to maximize power output
- 40% efficiency today, but we can sacrifice weight for more efficiency for TRESS
- \dot{M} 500W product is selected departure point



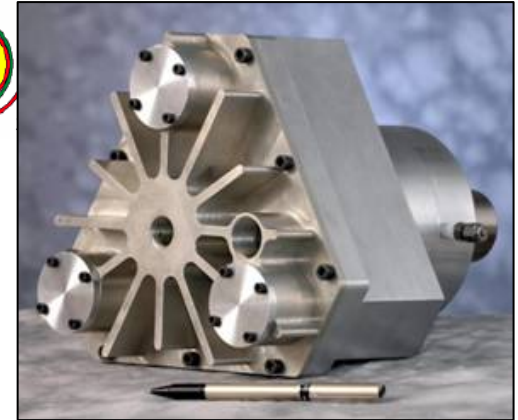
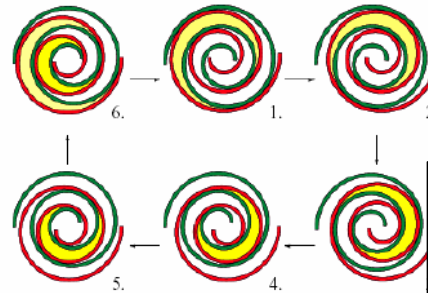
DARPA-Funded Microturboalternator for Portable Remote Electric Power

- Adding loop to “recycle” some water is one suggested approach to increasing efficiency by increasing mass flow throughput



Alternative Configurations for Optimizing Turbine Power

- Scroll expander offers 70% efficiency, however pressure ratio is limited
- Multiple units in series possible



- NASA Stirling engines for radioisotope systems
- 38% efficiency for 850°C to 90°C demonstrated

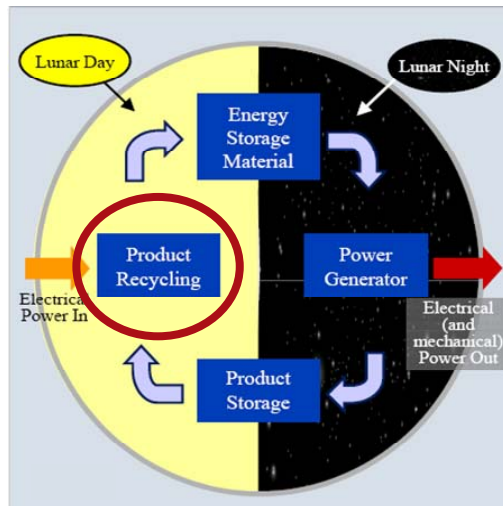
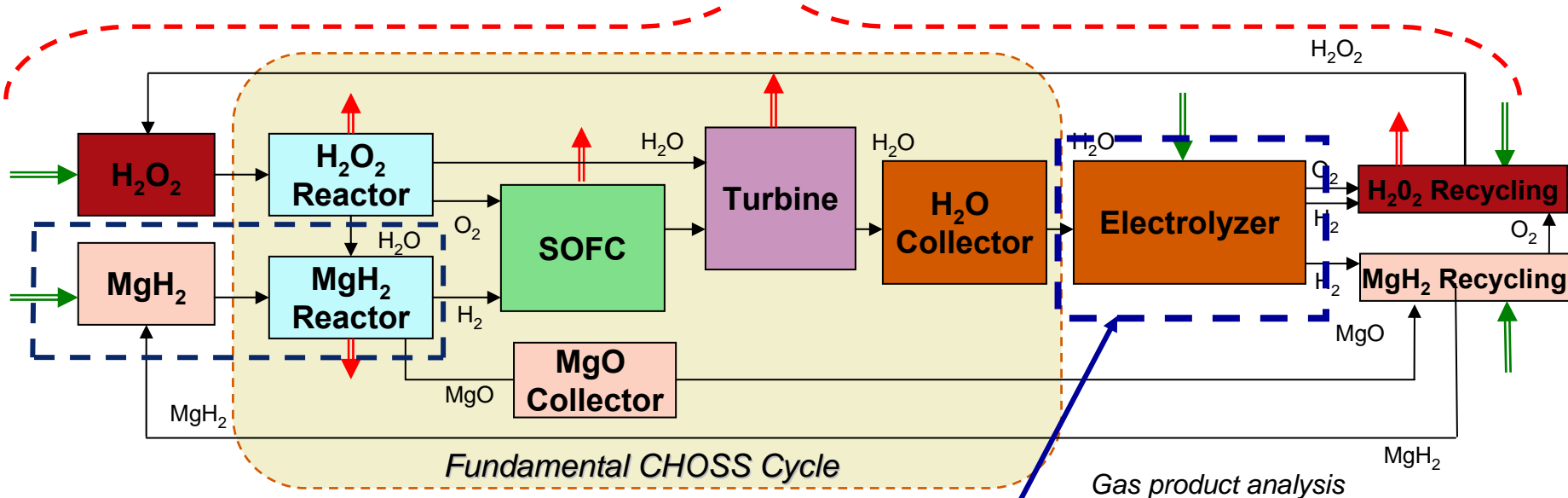
Micro Turbine Risk Summary



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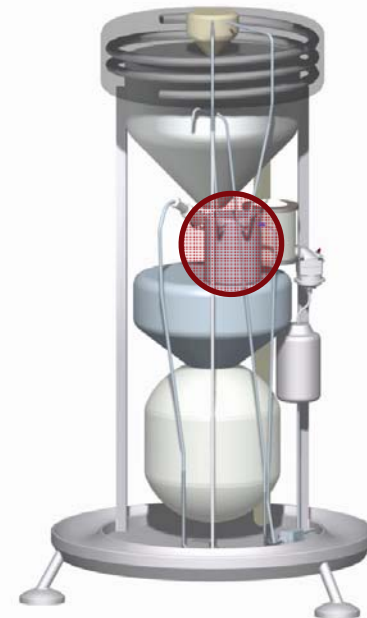
Technical Concerns for Power Turbine,	Effect on TRESS	Importance Level	Technical Risk	Mitigation Approach(s)
Corrosion- Steam at SOFC temperature and high pressure exposures can affect conventional metallic turbine materials like IN617, IN678, CSMSX-4, and X-35 which are Ni & Co based superalloys	Reduction in life, Increased maintenance frequency, Lower average efficiency	High	Med	<ul style="list-style-type: none"> •Need to understand long-term hot-corrosion behavior of superalloys at low levels of steam impurity, dissociation could cause H2 related problems. • Need to understand effects of mechanical stress on the material degradation of superalloys in a steam environment. •Take advantage of corrosion inhibitors and coatings in the oxidation and hot-corrosion protection of superalloys as they are developed for the power turbine industry
Gaspath gaps and seal leakage reduce efficiency	Small size demands close tolerances and low frictional losses for high efficiency	High	Med	Select best power system for low flow-rate and long life
Erosion from debris, bearing wear	Particles from the SOFC or other subsystems, in the closed loop system, can cause erosion	Med	Med	Careful selection and design of subsystems to trap small particles or insure that none are generated
Operability- Insuring effective turbine efficiency	Variation of turbine input; flowrate, steam quality, pressure, and temperature will affect turbine efficiency	High	High	Match turbine design architecture to the nominal operation conditions. Use controls and subsystems to allow turbine to be efficient at a broad range of operation situations.

Fundamental TRESS Cycle



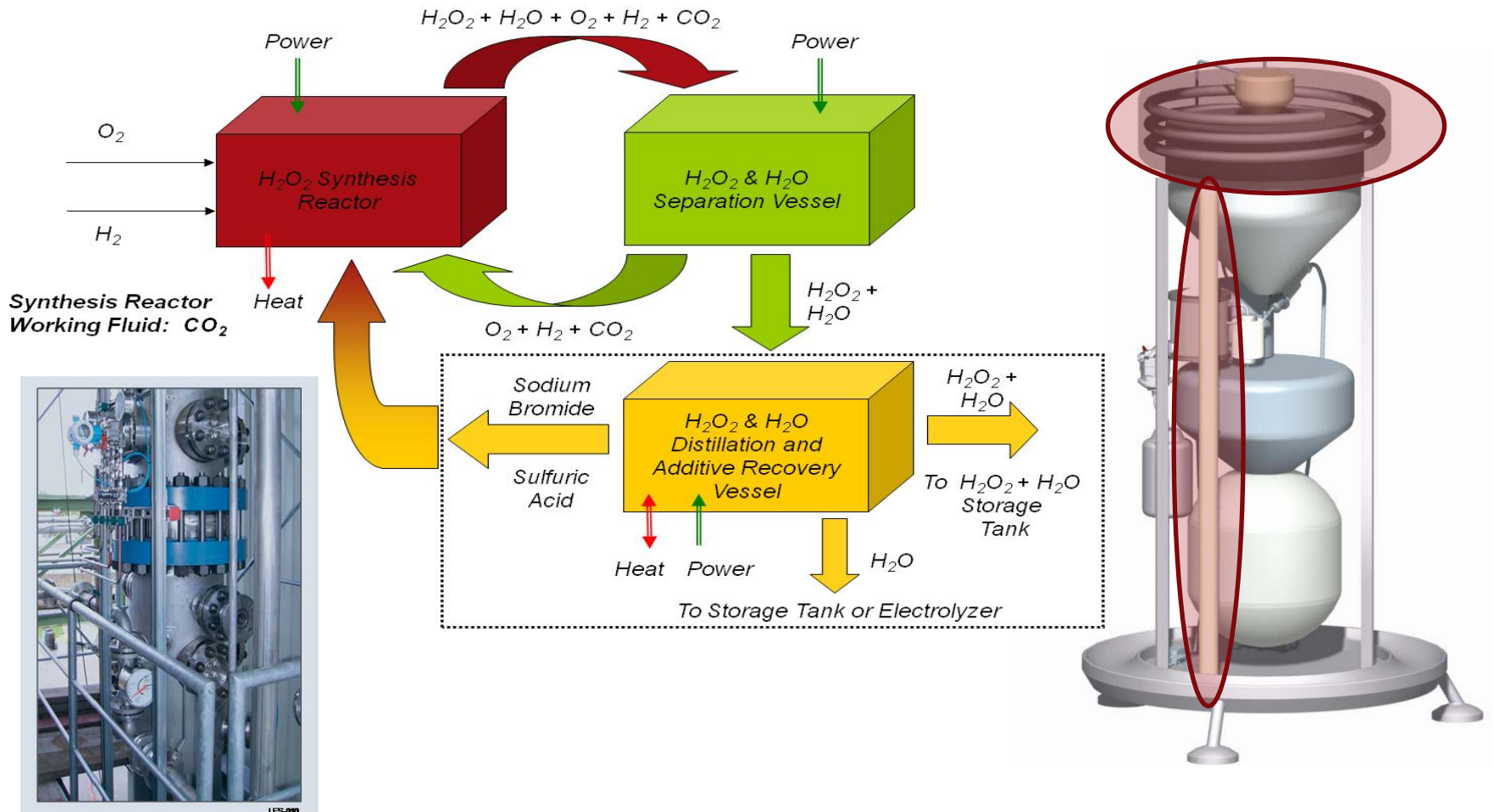
Electrolysis is the first step in the daytime recharge process

- Giner Electrochemical Systems 1,200 psi high pressure electrolyzer is baseline point of departure
- NASA GRC and DARPA funding
- Eliminates need for O₂ and H₂ compressors for H₂O₂ synthesis system

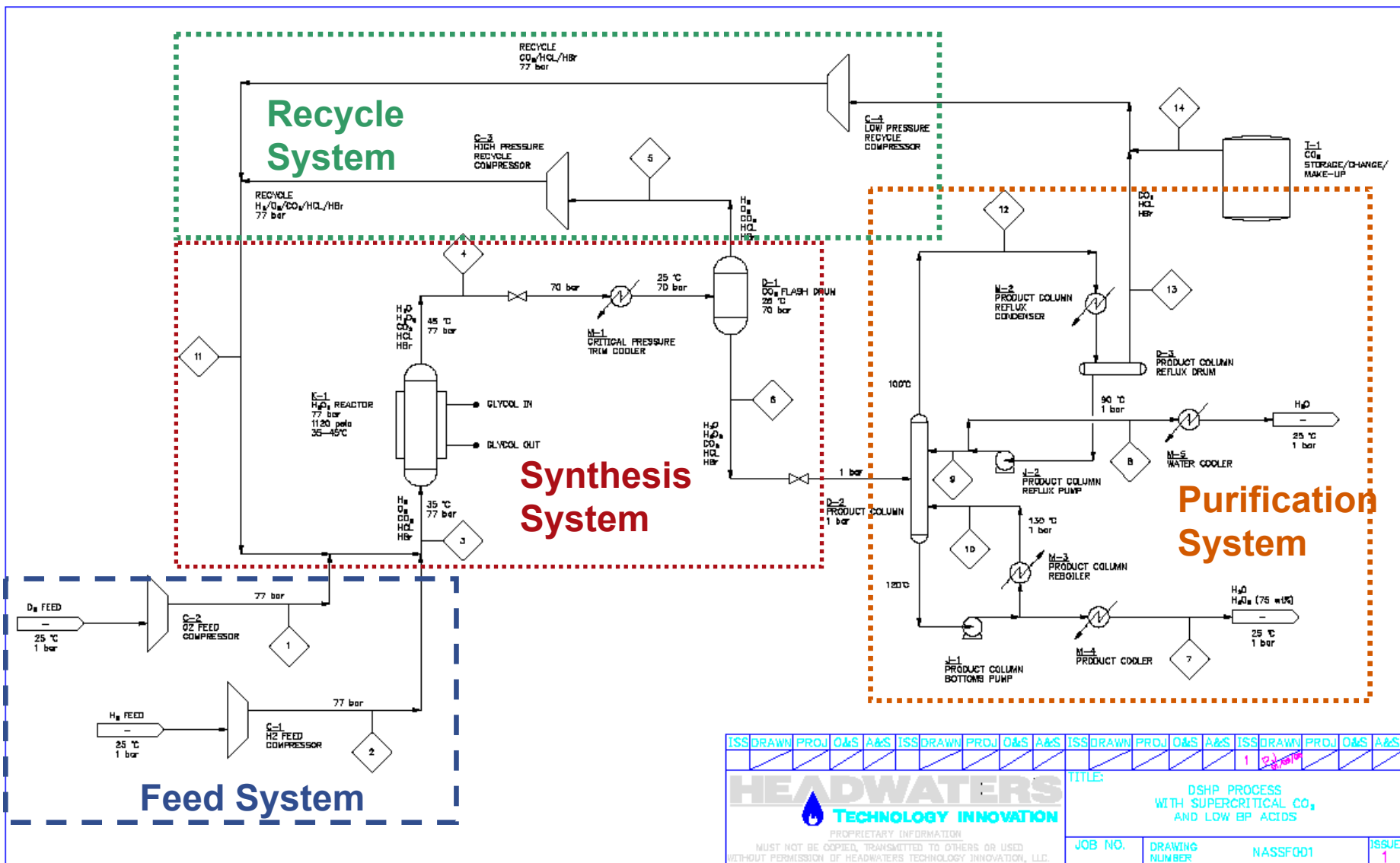


	Prototype
Specific power (W/kg)	386 (5100 Watts/13.2 kg)
Pressure (kPa gage)	8245 (1200 psig)
Efficiency at design point (at Higher Heat Value basis)	83.20% (@700 mA/cm ²)
Efficiency at 25% I _{max} (HHV basis)	86.40%
Efficiency at 50% I _{max} (HHV basis)	87.60%
Efficiency at 75% mA/cm ² (HHV basis)	86.00%

- Headwaters Technology Innovations direct synthesis process is baseline
- Industrial process uses methanol as substrate, TRESS uses supercritical CO_2



Finalized Process Flowchart



Energy balance

Cooling requirements

	KW	BTU/hr	kjoules/sec
Product Column Reflux Condenser	1.25	4,253	1.25
Critical Pressure Trim Cooler	0.58	1,967	0.58
H ₂ O ₂ Synthesis Reactor	6.33	21,610	6.33
Product Cooler	0.21	705	0.21
Water Cooler	0.08	262	0.08
H ₂ Intercooler	2.37	8,091	0.79
O ₂ intercooler	2.36	8,057	0.79

Heating requirements

	KW	BTU/hr	kjoules/sec
Product Column Reboiler	2.96	10,098	2.959

Power requirement, motors

	KW
H ₂ Feed Compressor	0.79
O ₂ Feed Compressor	0.79
High Pressure Recycle Compressor	0.79
Low Pressure Recycle Compressor	0.79
Product Column Bottoms Pump	0.79
Product Column Reflux Pump	0.79

Not required with high pressure electrolysis

Summary of Equipment Weight (2X of TRESS)

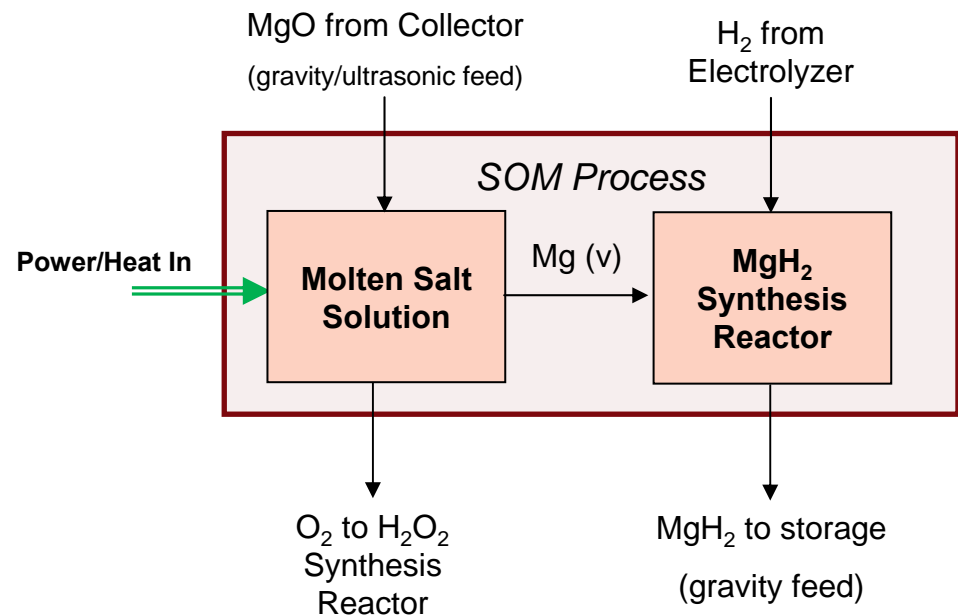
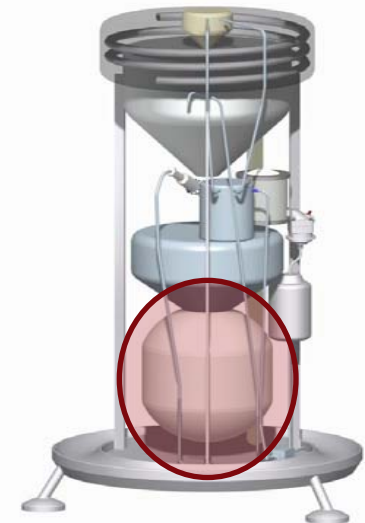
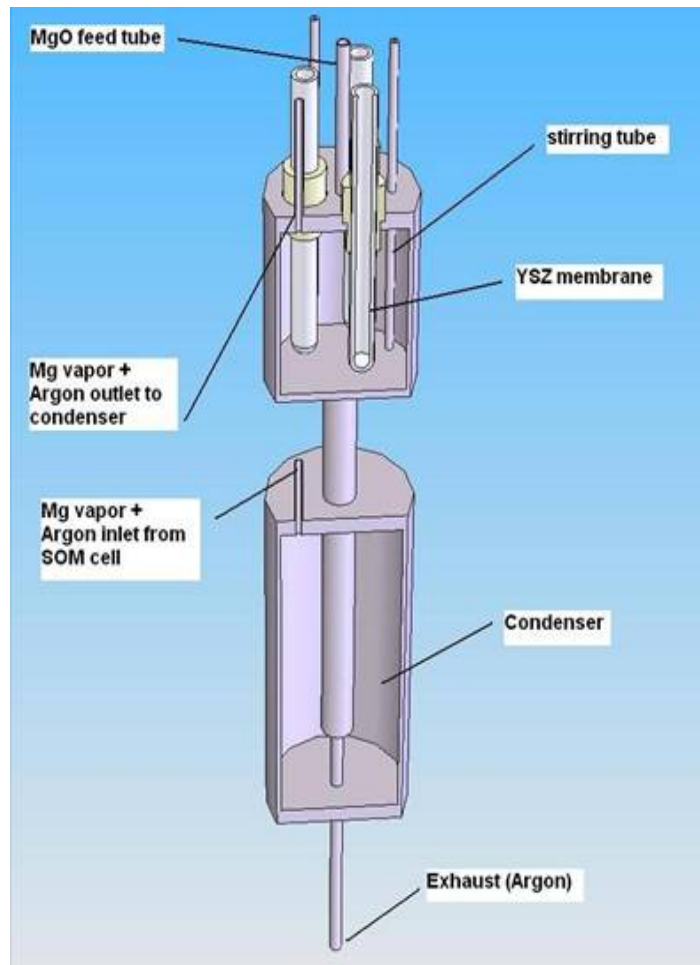


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Weight, KGS		
K-1	H ₂ O ₂ Synthesis Reactor	43.40
C-1	H ₂ Feed Compressor	107.53
C-2	O ₂ Feed Compressor	107.53
C-3	High Pressure Recycle Compressor	29.33
C-4	Low Pressure Recycle Compressor	29.33
D-1	CO ₂ Flash Drum	1.88
D-2	Product Column	9.55
D-3	Product Column Reflux Drum	1.88
M-1	Critical Pressure Trim Cooler	4.53
M-2	Product Column Reflux Condenser	5.24
M-3	Product Column Reboiler	1.08
M-4	Product Cooler	2.27
M-5	Water Cooler	0.74
J-1	Product Column Bottoms Pump	4.55
J-2	Product Column Reflux Pump	4.55
T-1	CO ₂ Make-up Tank	3.16
Frame - structural	allowance	25.00
Valves, instruments, computer etc	allowance	35.00
Interconnecting piping, contingency	allowance	45.00
TOTAL WEIGHT		461.52 KGS

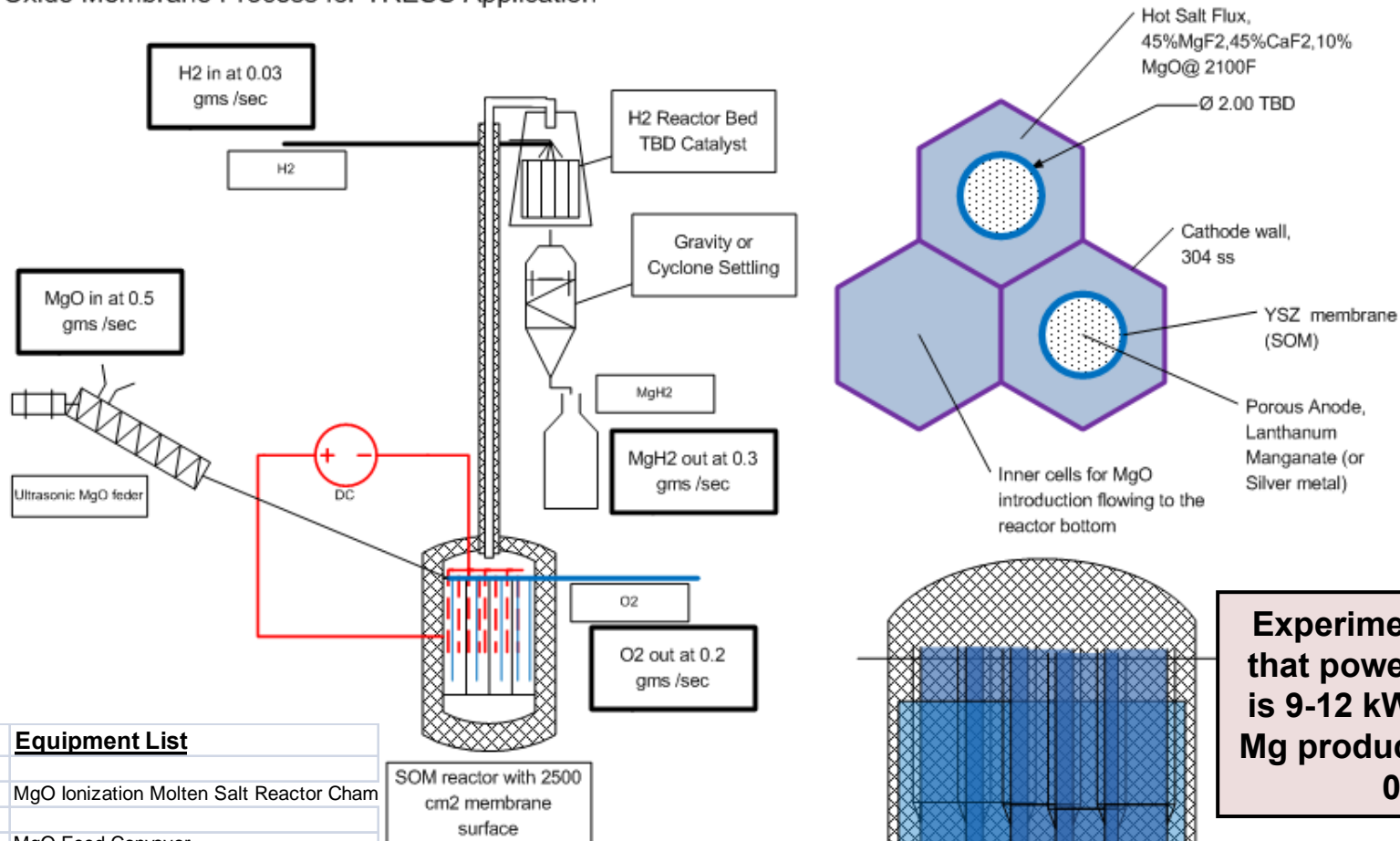
Not required with high pressure electrolysis

Boston University Solid Oxide Membrane (SOM) process is baseline for MgO decomposition



MgH₂ Recycle System Schematic V2.0

Solid Oxide Membrane Process for TRESS Application

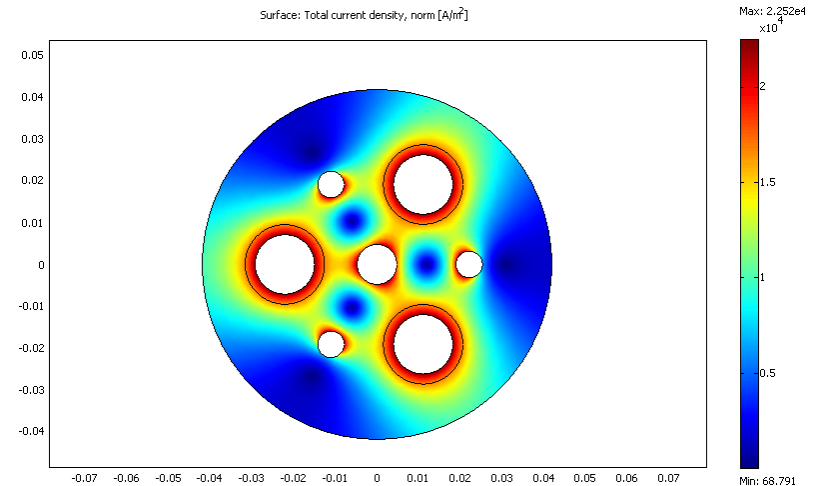
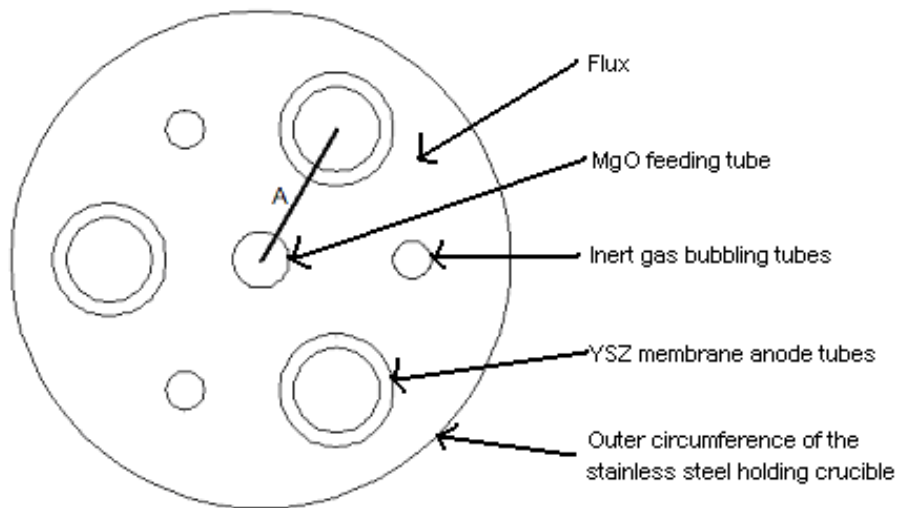


Equipment List

1	MgO Ionization Molten Salt Reactor Cham
2	MgO Feed Conveyor
3	H ₂ feed metering device
4	Anode/Cathode DC electrical input
5	Resistance heating input
6	Mg Vertical Product Column
7	H ₂ / Mg Reactor Flash Drum
8	Product Collection Drum

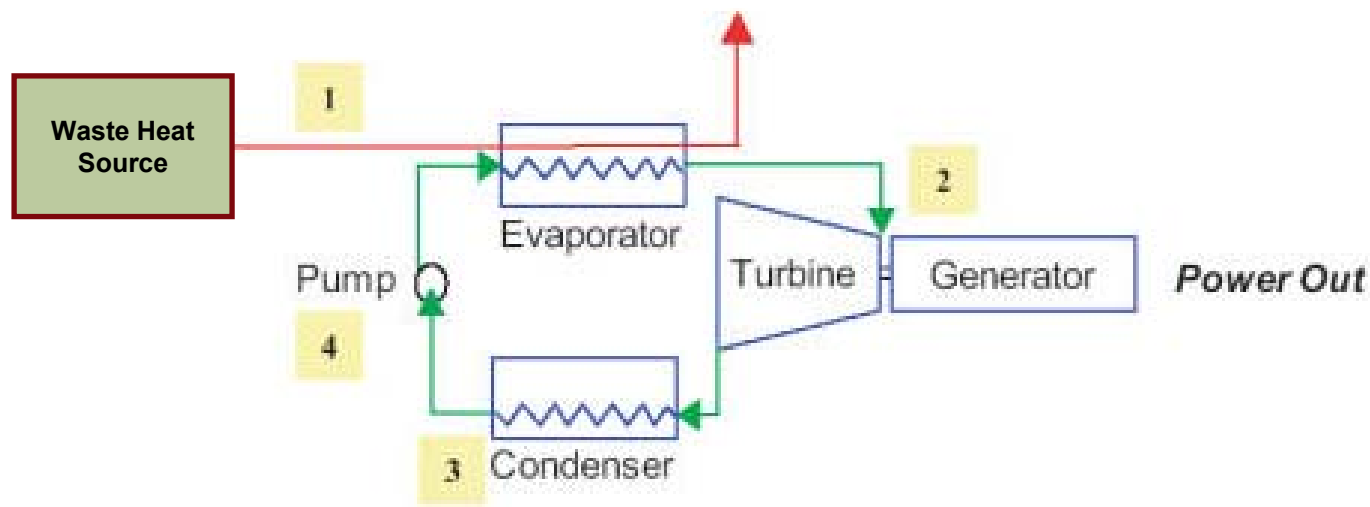
Experiments indicate that power consumed is 9-12 kW-h per kg of Mg produced @ 5V (+/- 0.5V)

- Key issue is maintaining a uniform electrical (and thermal) environment in array of SOM tubes/reactor sections



Cell setup used to model total current density at various boundary conditions

- ORC bottoming cycle may be used to extract additional energy from H₂O₂ synthesis reactor cooling loop
- Use of second fluid and temperature difference from reactor (1,150°C) to shaded lunar heat sink
- Low efficiency expected due to indirect heat exchange (~20%), but small system does not add significant weight



SOM Process + MgH₂ Synthesis Risk Summary

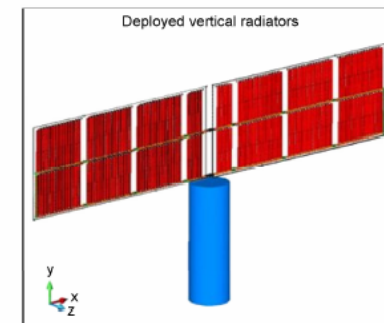
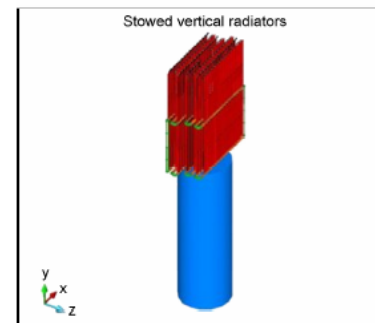
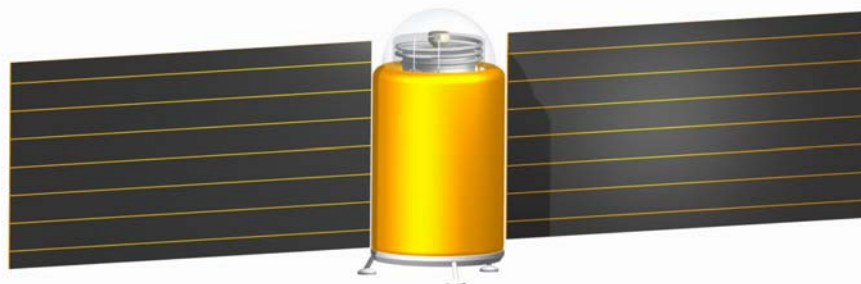


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Risk Items	Effect(s)	Importance/ Likely-hood	Technical Risk	Mitigation Measures
Anode Degradation	Efficiency, weight, life, maintenance	High	Med	Good area for near-term understanding, characterization of anode material types
Containment Vessel Corrosion	maintenance, life	High	High	Investigate alternatives- material optimization, coatings, alloys.; surface temp.
Unacceptable Thermal Energy Loss	Eff.	Med	Med	Insulate, combine with compatible process, utilize waste heat
YSZ Membrane Durability	Life, Eff., size, maint., durability	High	High	Examine post-exposure mechanical and physical characteristics, if unacceptable determine optional size geometry and temperature membrane materials
Ionic Flux Stability	Eff., life, maint.	Med	Med	SOM Specific design/analysis
Overall-System Size and Weight	Wt., Volume	Med	Med	To find sub-synergies and project effects of the future micro-scaling and membrane technologies
Product purity	Performance loss	Low	Low	Determine whether the contaminants are adverse and if they increase over time.
Ineffective gas phase MgH ₂ synthesis	Incorrect chemistry	High	High	Not typical given gas phase Mg – bench-scale tests to verify with SOM

Heat Rejection Scheme

NASA CR – 2006-214388¹ describes a potential system for heat rejection of temperatures in the range $\sim 450\text{K}$ (177°C).



Daytime Waste Heat, Day = Night
(5kW system, 60% efficiencies for turbine and SOFC, 75% H_2O_2)

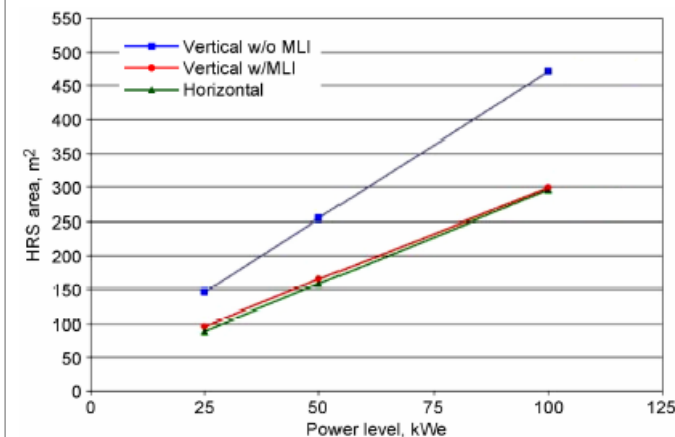
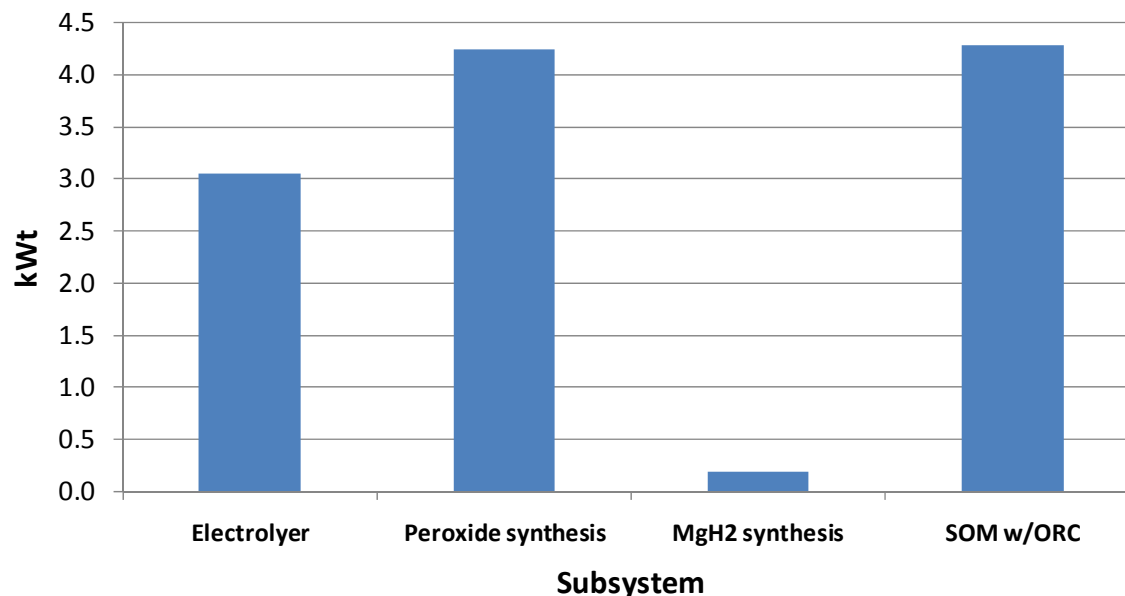
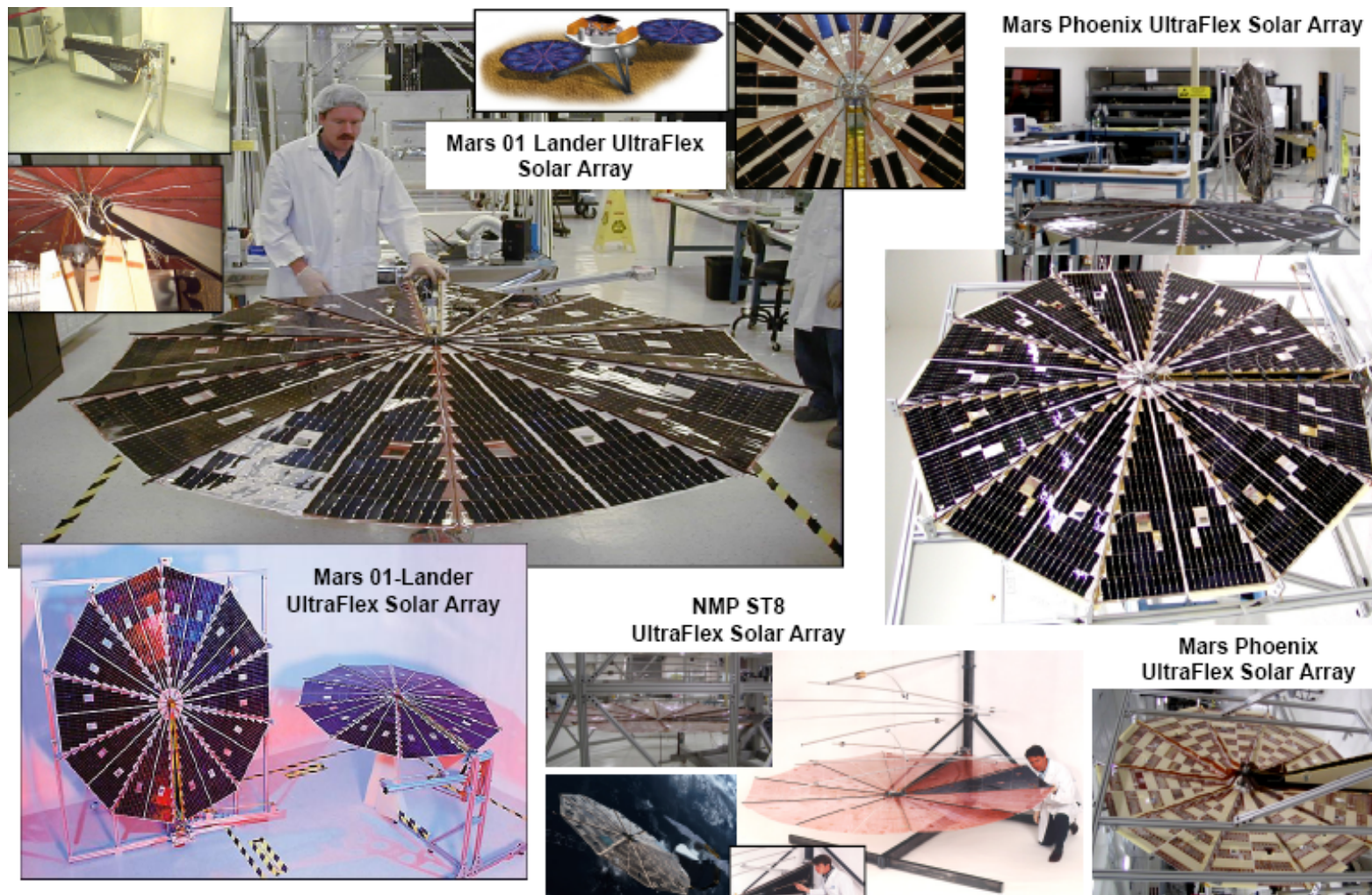


Figure 13.—HRS radiator radiative area versus power level.

A ~6 meter diameter Single-Wing UltraFlex unit of 14-18 kW will be able to provide the necessary power for the daytime regeneration cycle of TRESS.



Risk Items	Effect(s)	Importance/ Likely-hood	Technical Risk	Mitigation Measures
Inaccuracy in flow control, particularly during system transients	Reduced efficiency, offset thermal balance, unwanted products can accumulate contaminants	High	High	Comprehensive closed-loop control architecture development. Extensive testing and sensitivity examination
Thermal balance variations, particularly during transients	System efficiency, weight, life	High	Med	Thermal controls development and testing – sensitivity assessment. Environmental tests
Accumulation of contaminants	Efficiency, life reduction	High	High	Subsystem testing to insure purity, system testing to assess impacts

SYSTEM	TRL today (on earth)	TRL today (lunar)	Risk to TRL 6 by 2015
H2O2 Storage	9	2	L
MgH2 Storage	9	2	L
H2O2 Decomposition Reactor	9	3	L
MgH2 + H2O Reactor	4	2	L
SOFC and Turbine	5	3	M
Water Electrolysis	9	6	L
MgH2 Synthesis	3	1 - 2	M/H
H2O2 Synthesis	9	1 - 2	M/H
System Integration and Operation			H

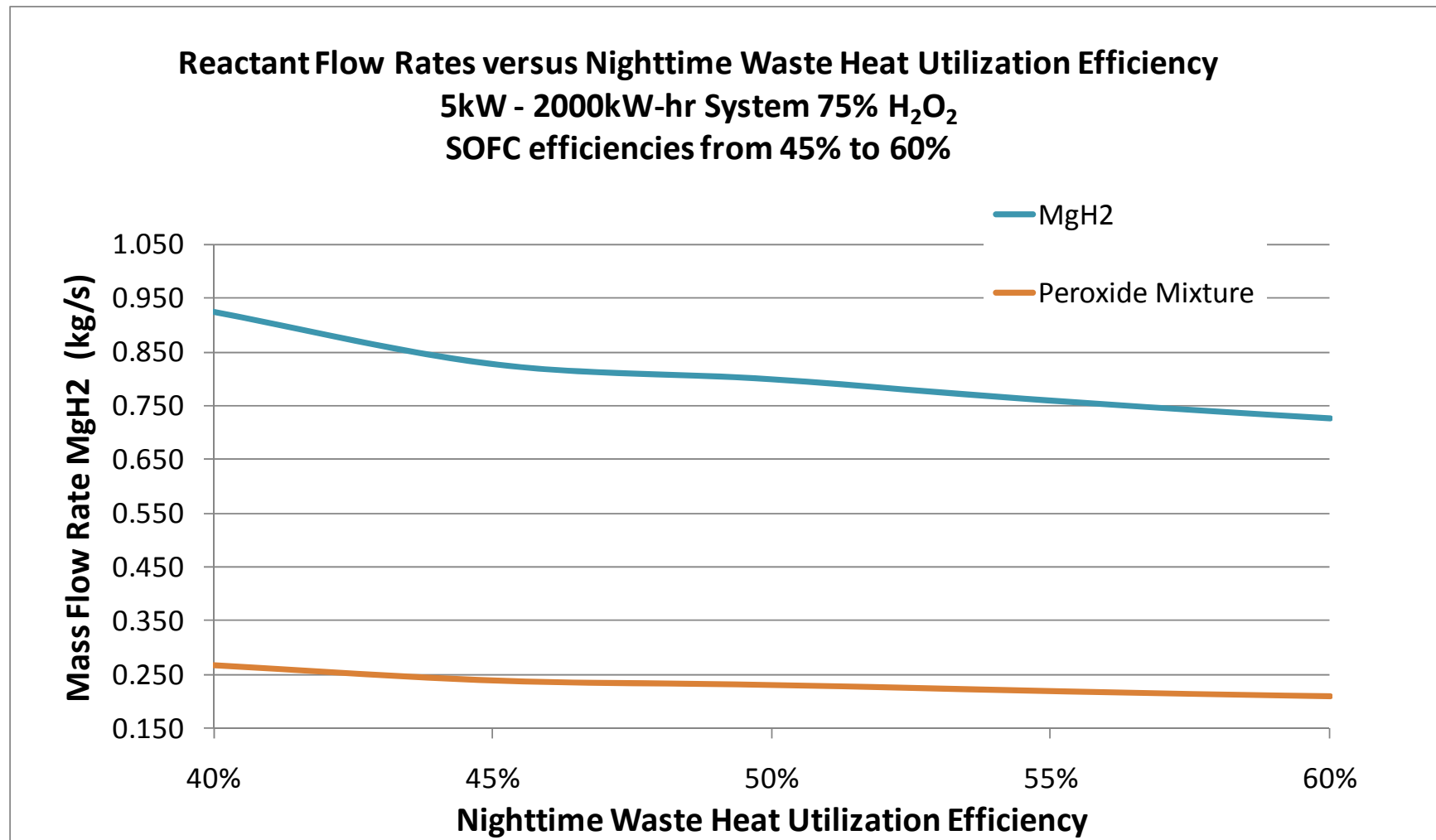
Variables used in parametric analysis:

- Percent hydrogen peroxide concentration in water (50% and 75%)
- System power level (2, 3.5 and 5 kW)
- System energy storage (100kWh to 2000kwh) or up to 400 hours
- Regeneration time as a function of power generation time (1X and 2X)
- SOFC efficiency (45% to 60%)
- Nighttime waste heat efficiency – defined as the thermal efficiency of the device extracting power from the 1000°C steam produced by the SOFC between a pressure of 15atm and 0.055atm. (40% to 60%)
 - This may be a series of microturbines (turbo alternators), Stirling heat engines, expanders, or a combination thereof.

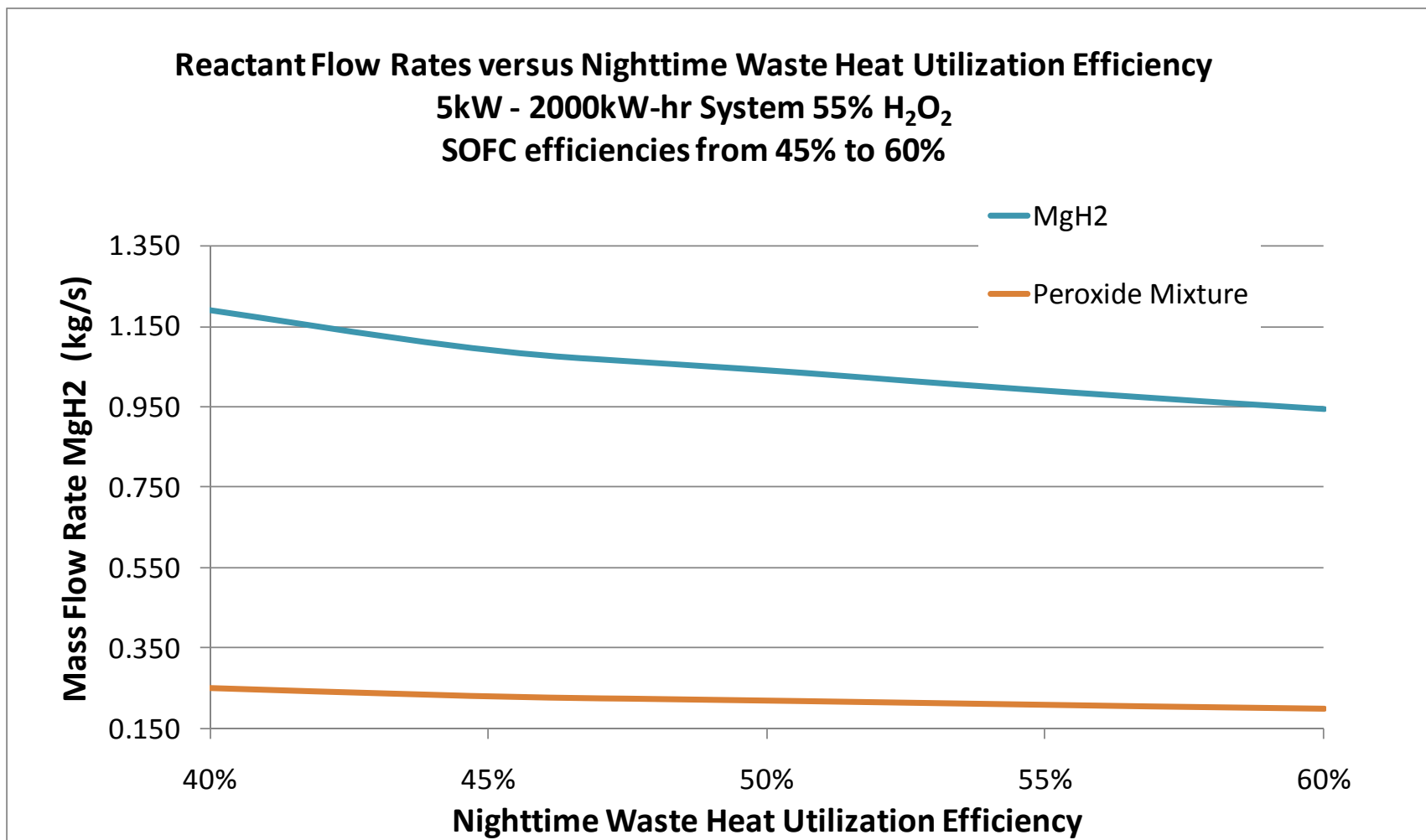
Key Figures of Merit:

- **System Flow Rates**
- **Overall TRESS system mass**
- **Energy-in/Energy-out efficiency – overall a complete power-out/regeneration cycle**
- **Power-in requirements**
- **System mass distribution by major subsystem**
 - **Reactants as a percent of total system mass**

Reactant Flow Rates – 5kW, 75% Peroxide



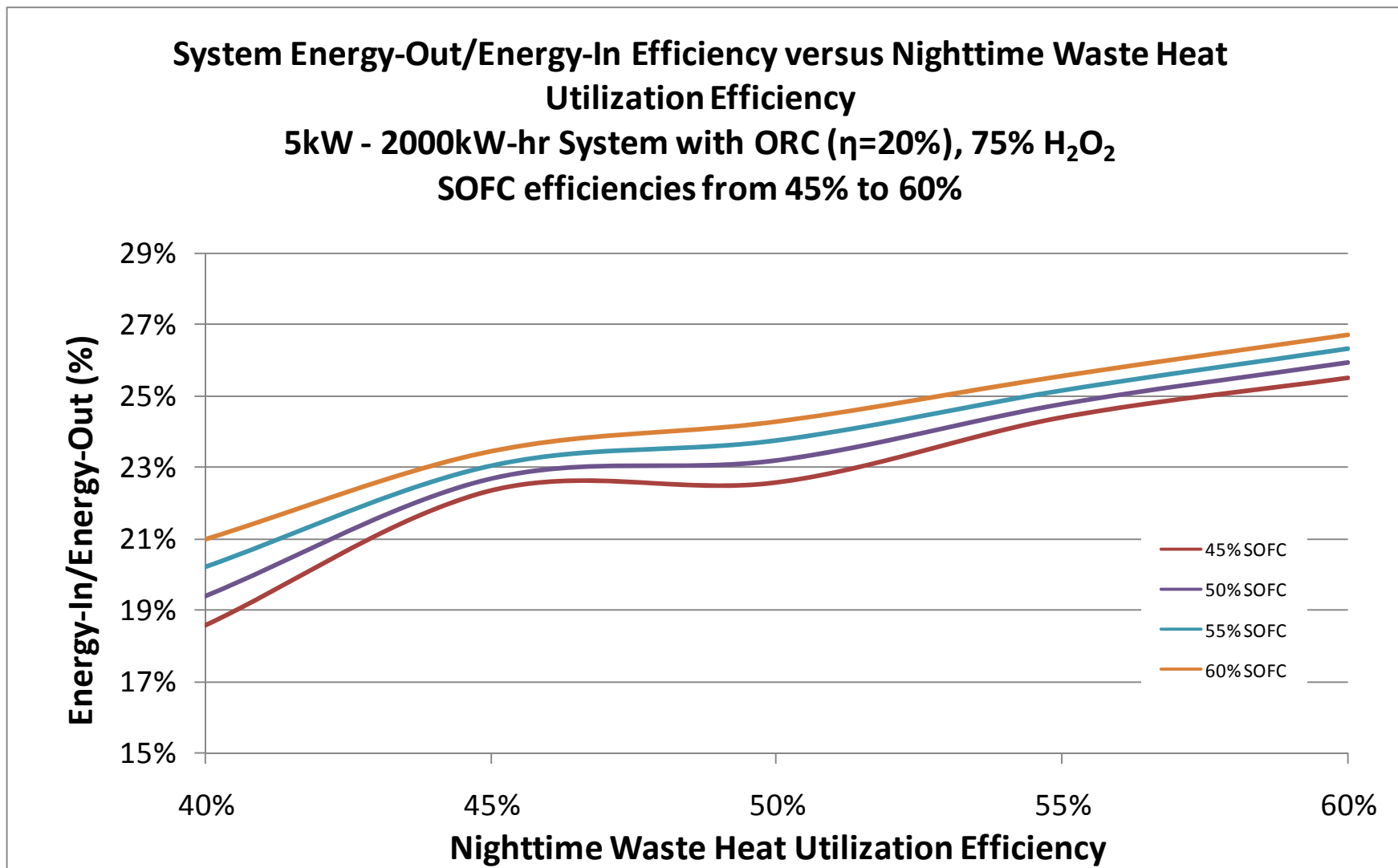
Reactant Flow Rates – 5kW, 55% Peroxide



Overall System Energy Efficiency with ORC



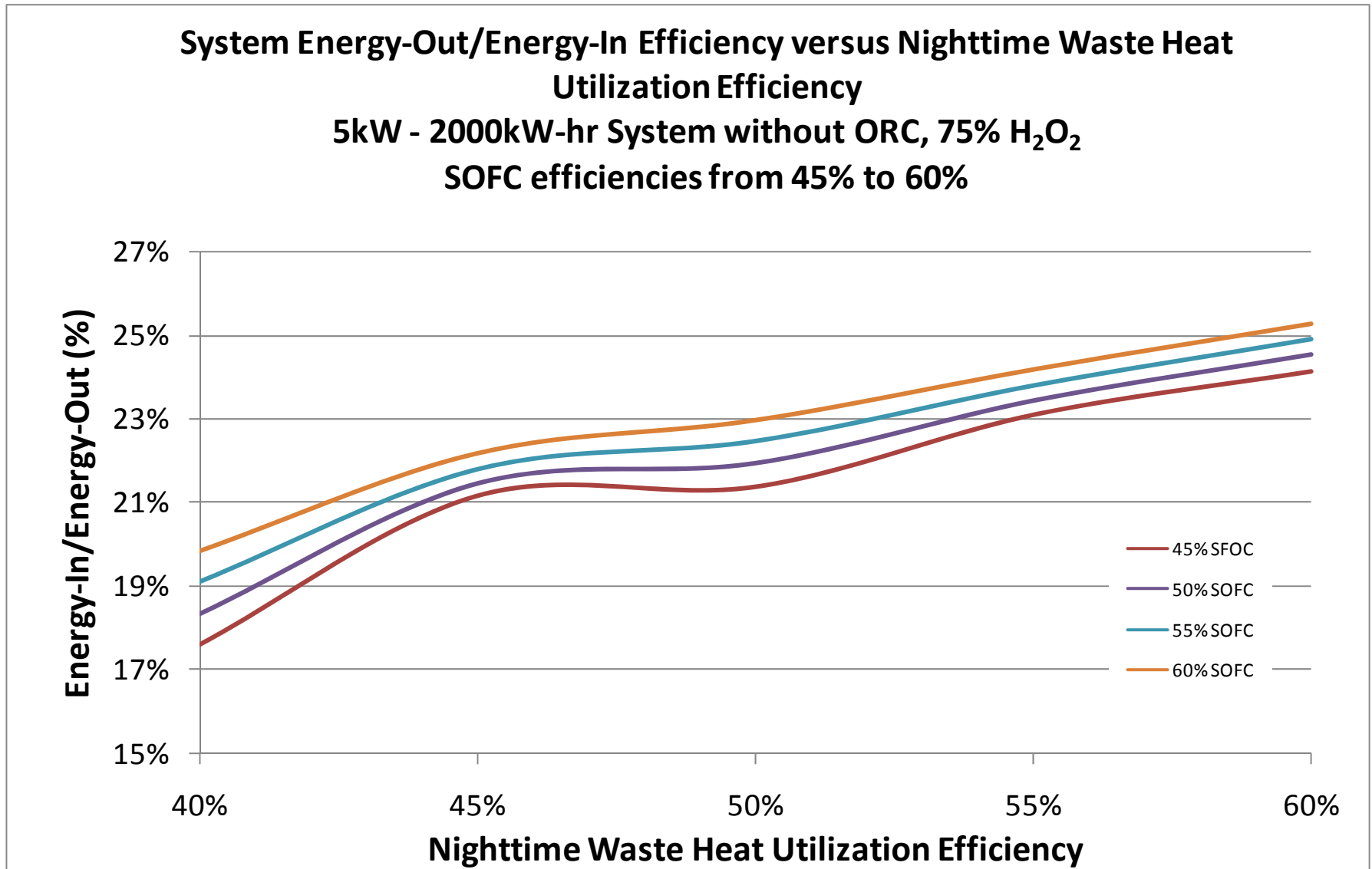
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Overall System Energy Efficiency w/o ORC



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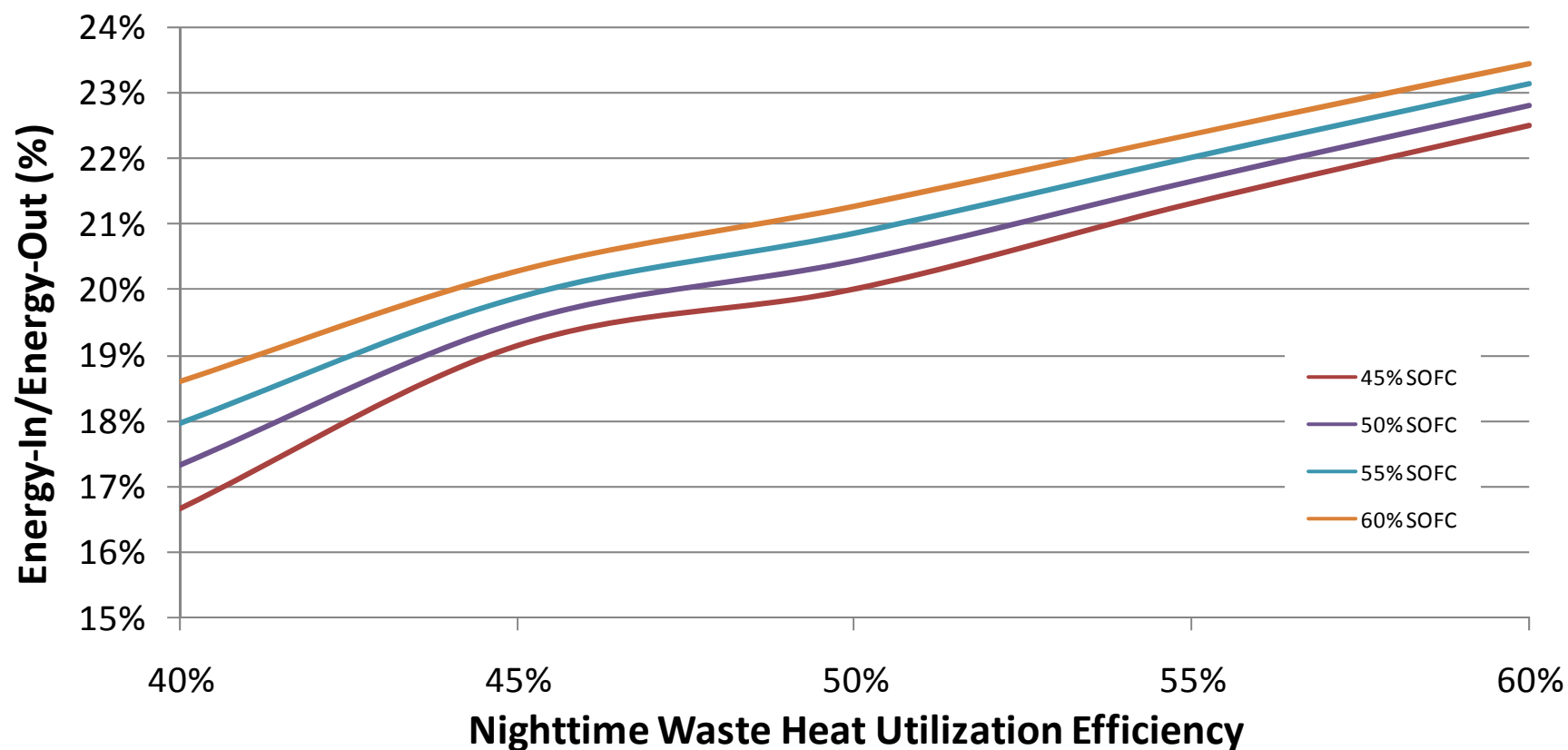
Effect of Reduced Peroxide Concentration



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System Energy-Out/Energy-In Efficiency versus Nighttime Waste Heat Utilization Efficiency

5kW - 2000kW-hr System with ORC ($\eta=20\%$), 55% H_2O_2
SOFC efficiencies from 45% to 60%



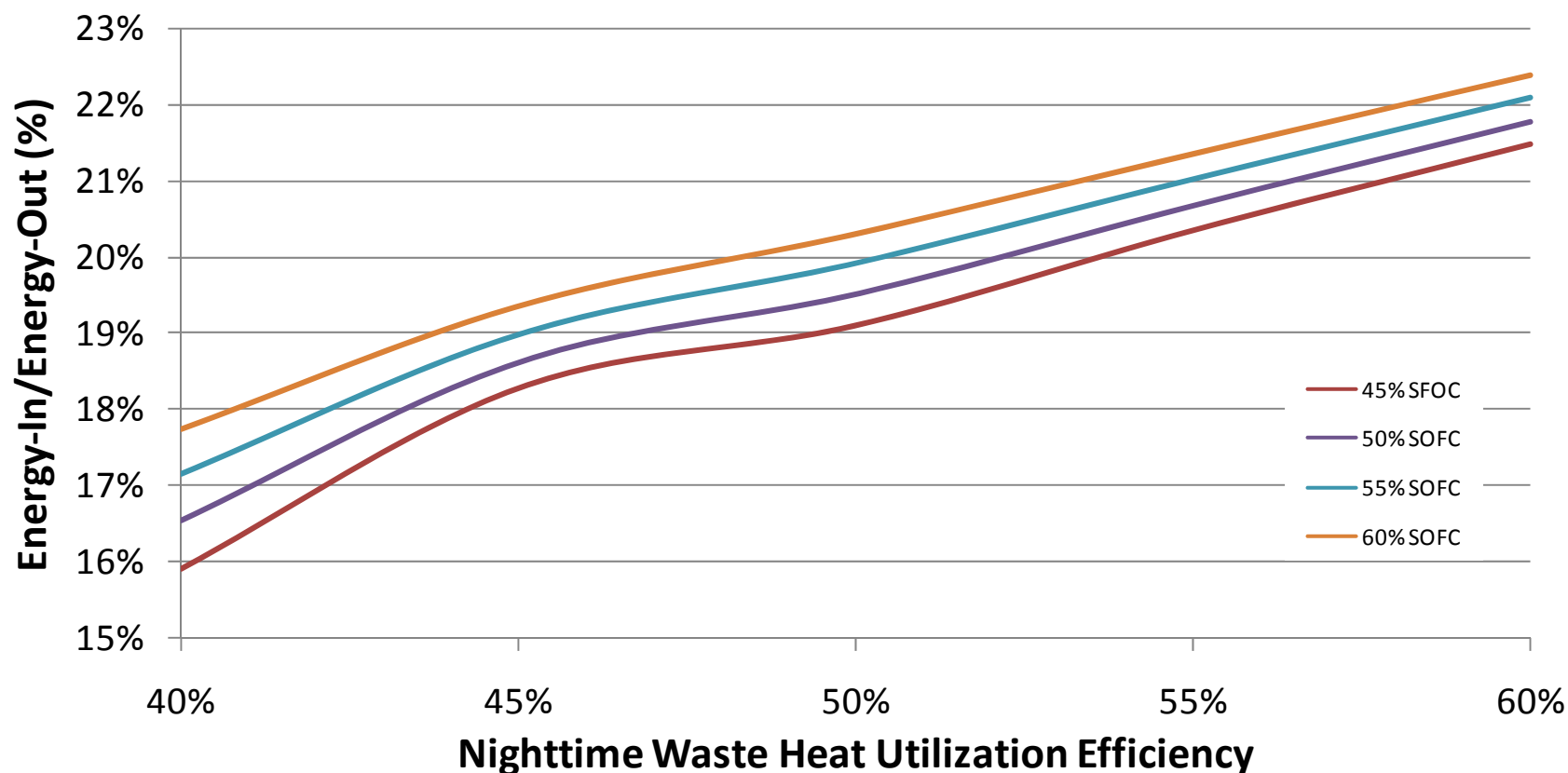
Effect of Reduced Peroxide Concentration

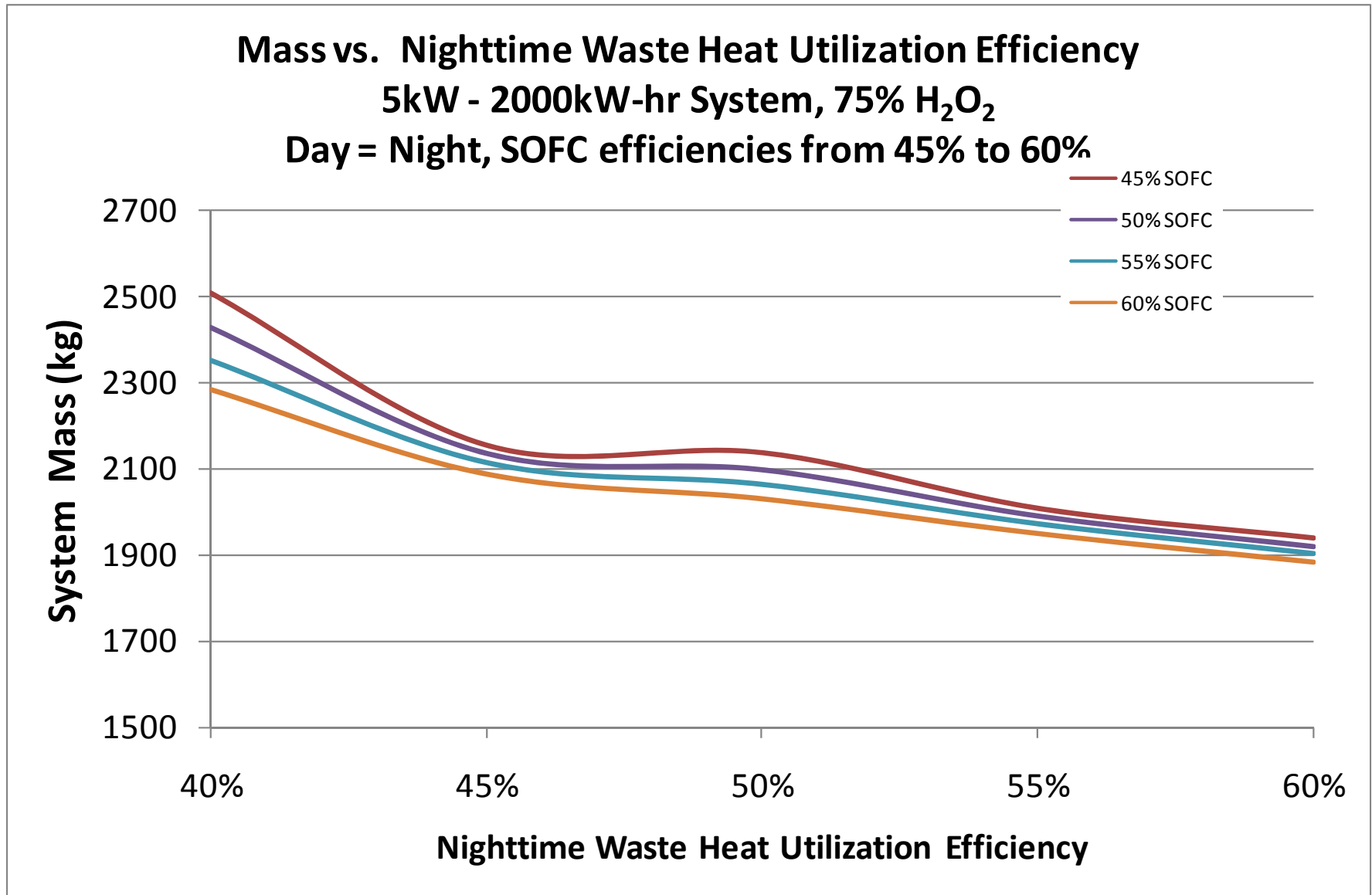


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System Energy-Out/Energy-In Efficiency versus Nighttime Waste Heat Utilization Efficiency

5kW - 2000kW-hr System without ORC, 55% H_2O_2
SOFC efficiencies from 45% to 60%

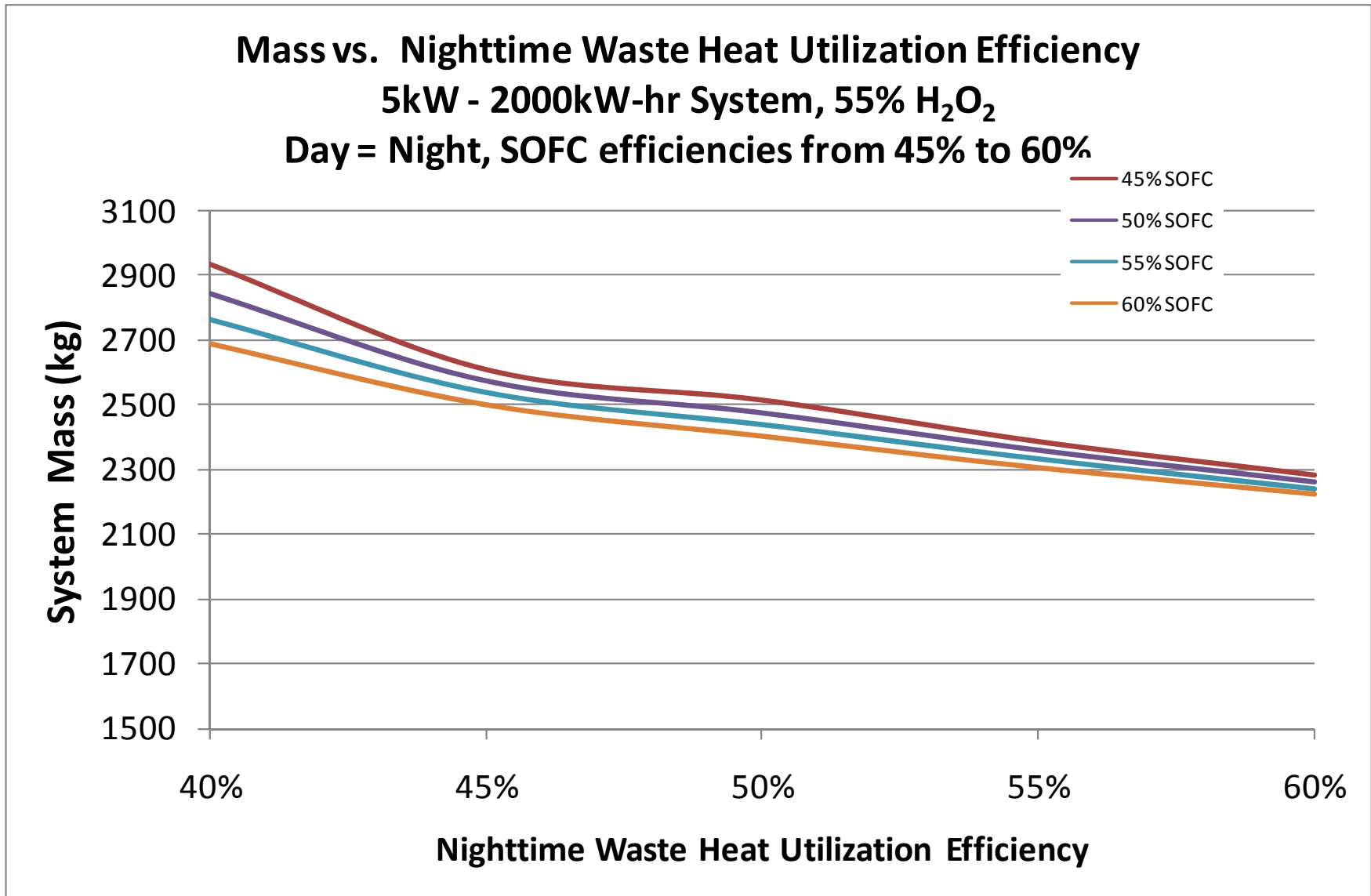




System Mass Sensitivity (5kW, 55% Peroxide)



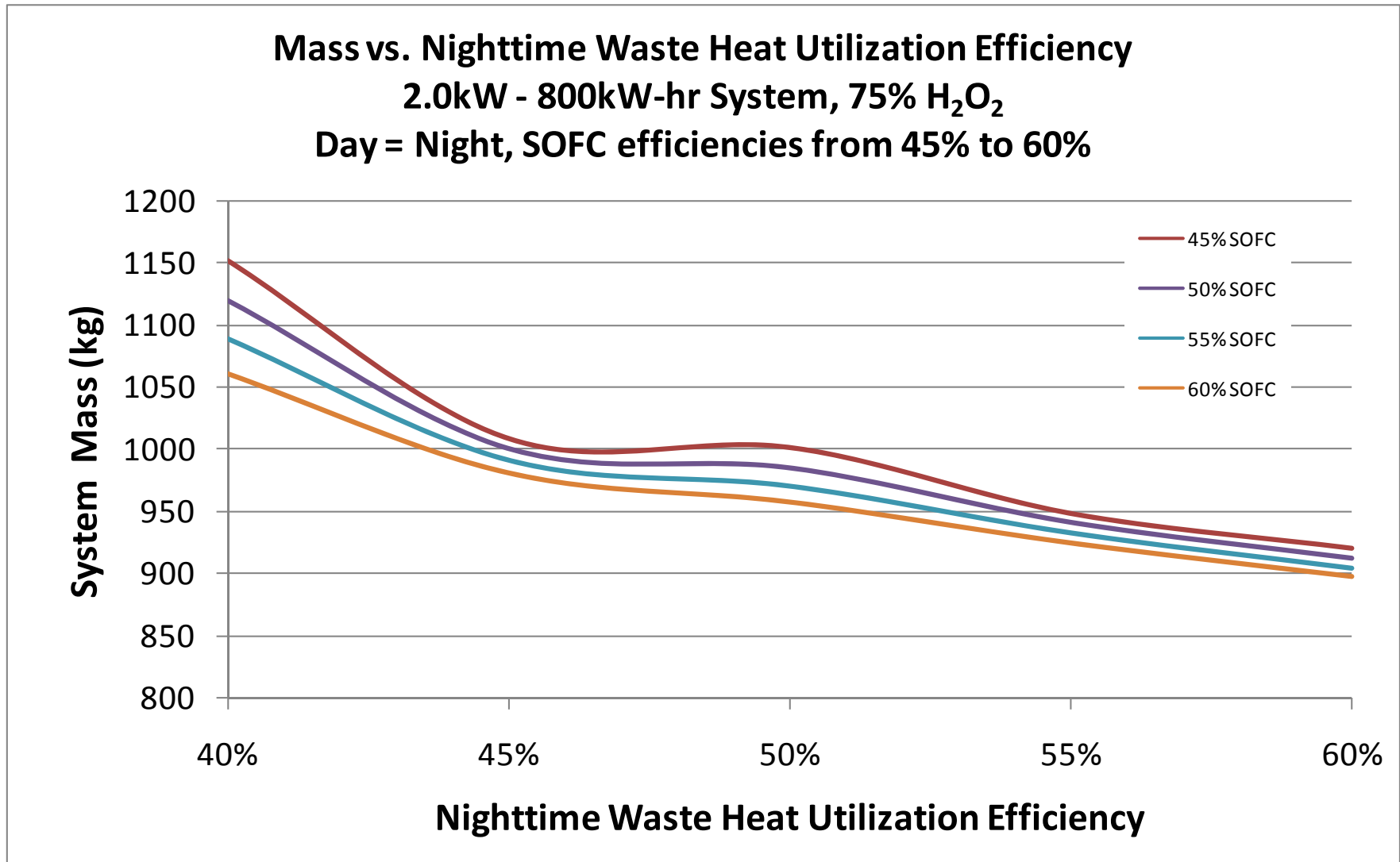
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System Mass Sensitivity (2kW, 75% Peroxide)



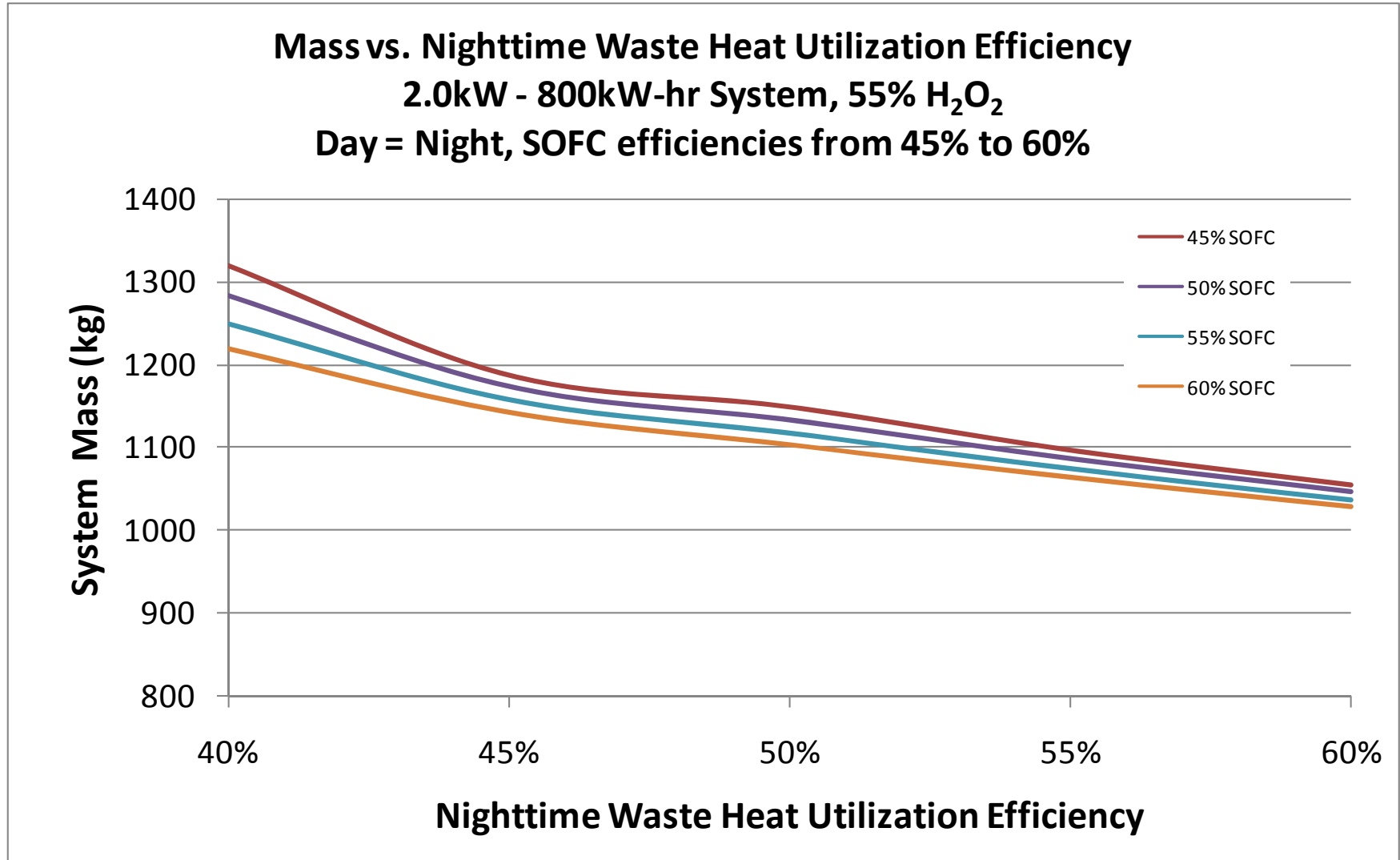
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System Mass Sensitivity (2kW, 55% Peroxide)



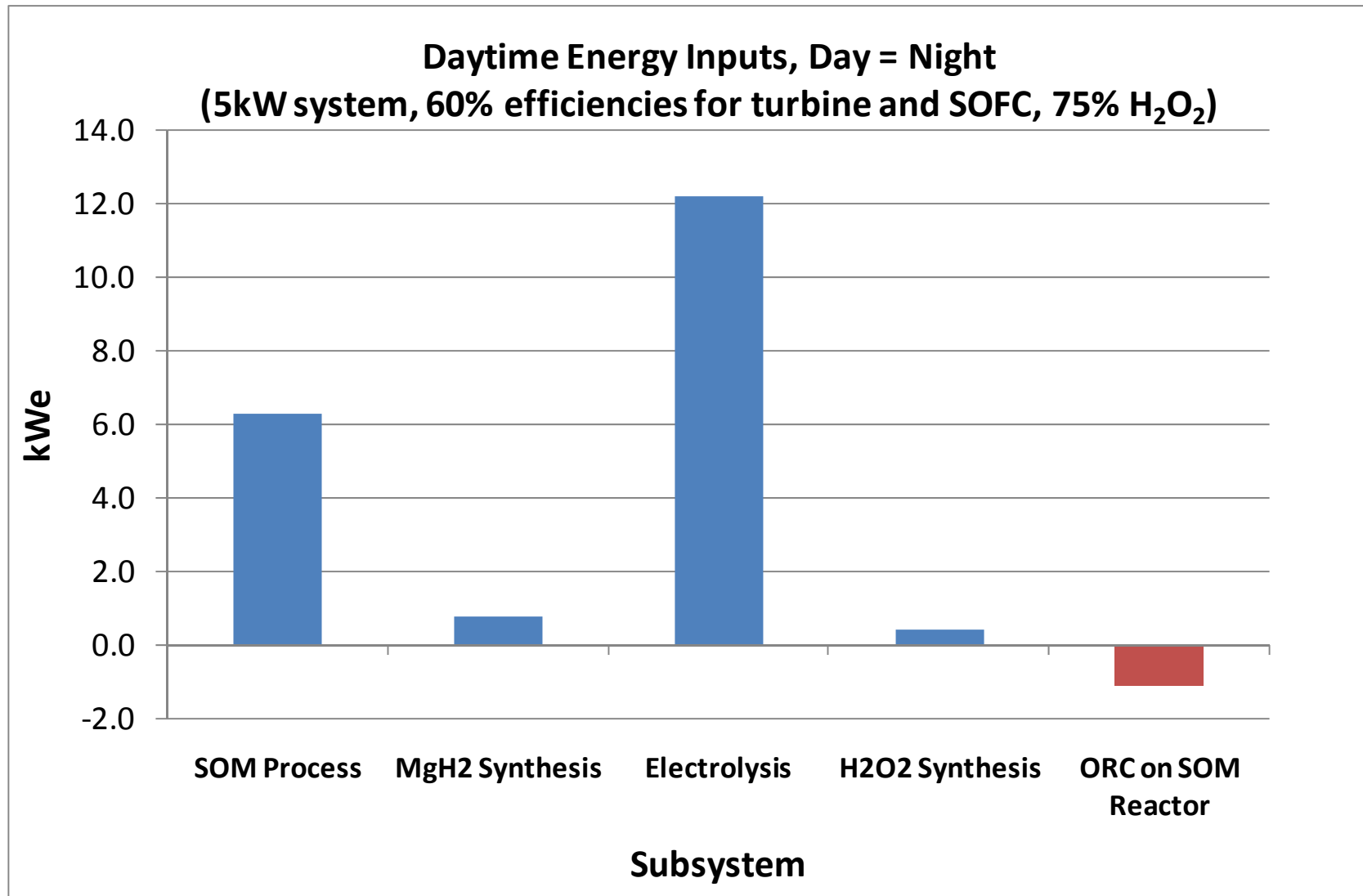
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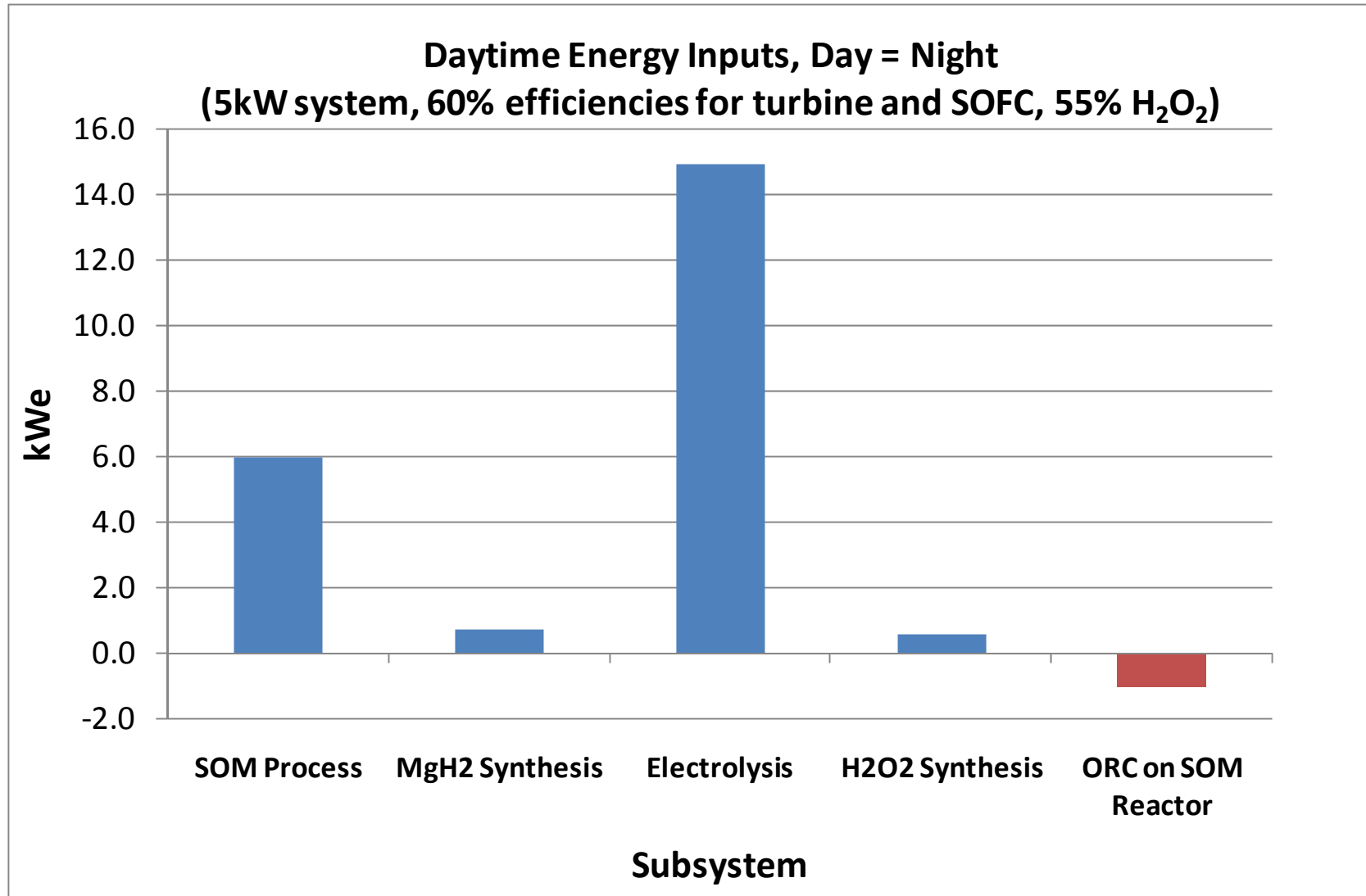
Energy Input Requirements Day = Night duration



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Energy Inputs for 55% Peroxide

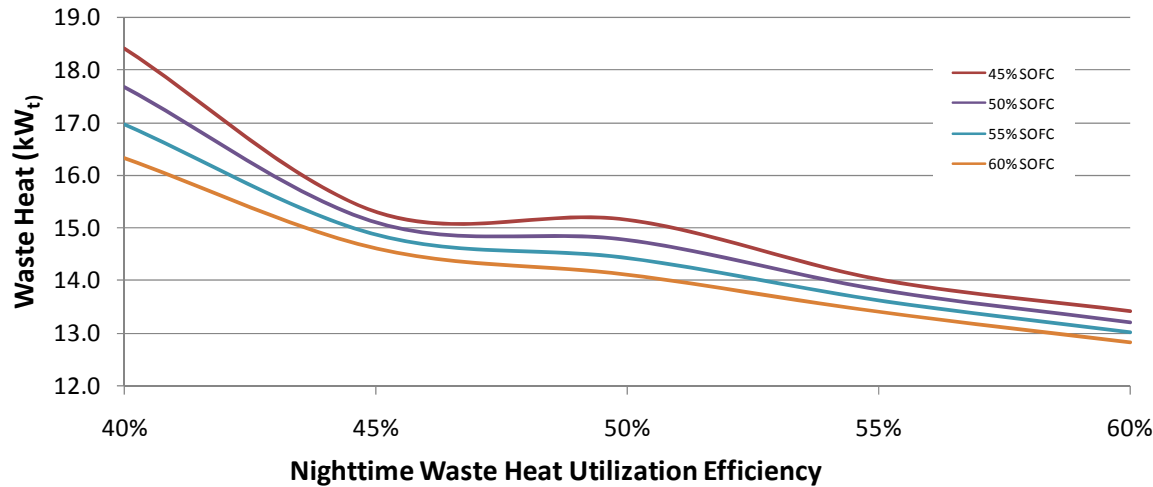


Daytime Waste Heat (75% Peroxide)

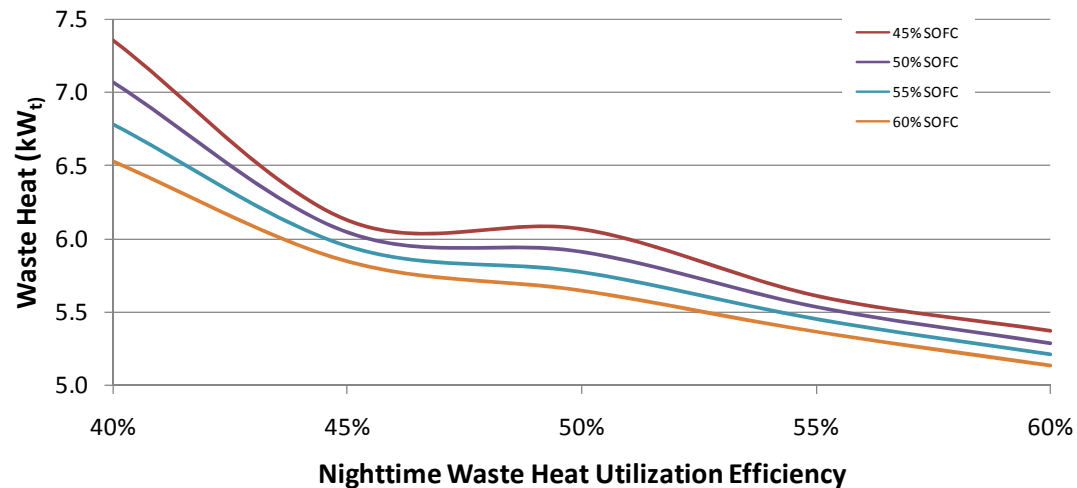


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Daytime Waste Heat vs. Waste Heat Utilization Efficiency
5kW - 2000kW-hr System with ORC with $\eta=20\%$, 75% H_2O_2
Day = Night, SOFC efficiencies from 45% to 60%



Daytime Waste Heat vs. Waste Heat Utilization Efficiency
2.0kW - 800kW-hr System with ORC with $\eta=20\%$, 75% H_2O_2
Day = Night, SOFC efficiencies from 45% to 60%

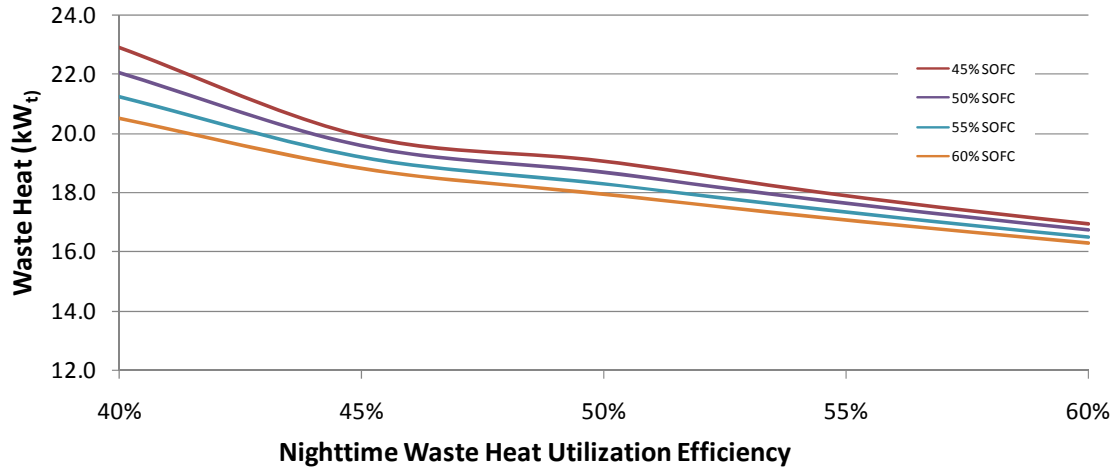


Daytime Waste Heat (55% Peroxide)

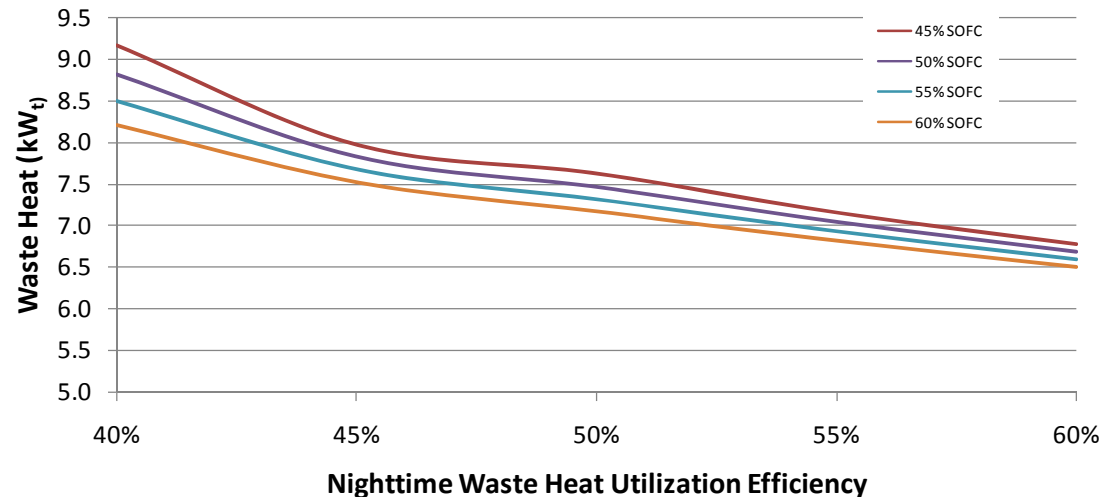


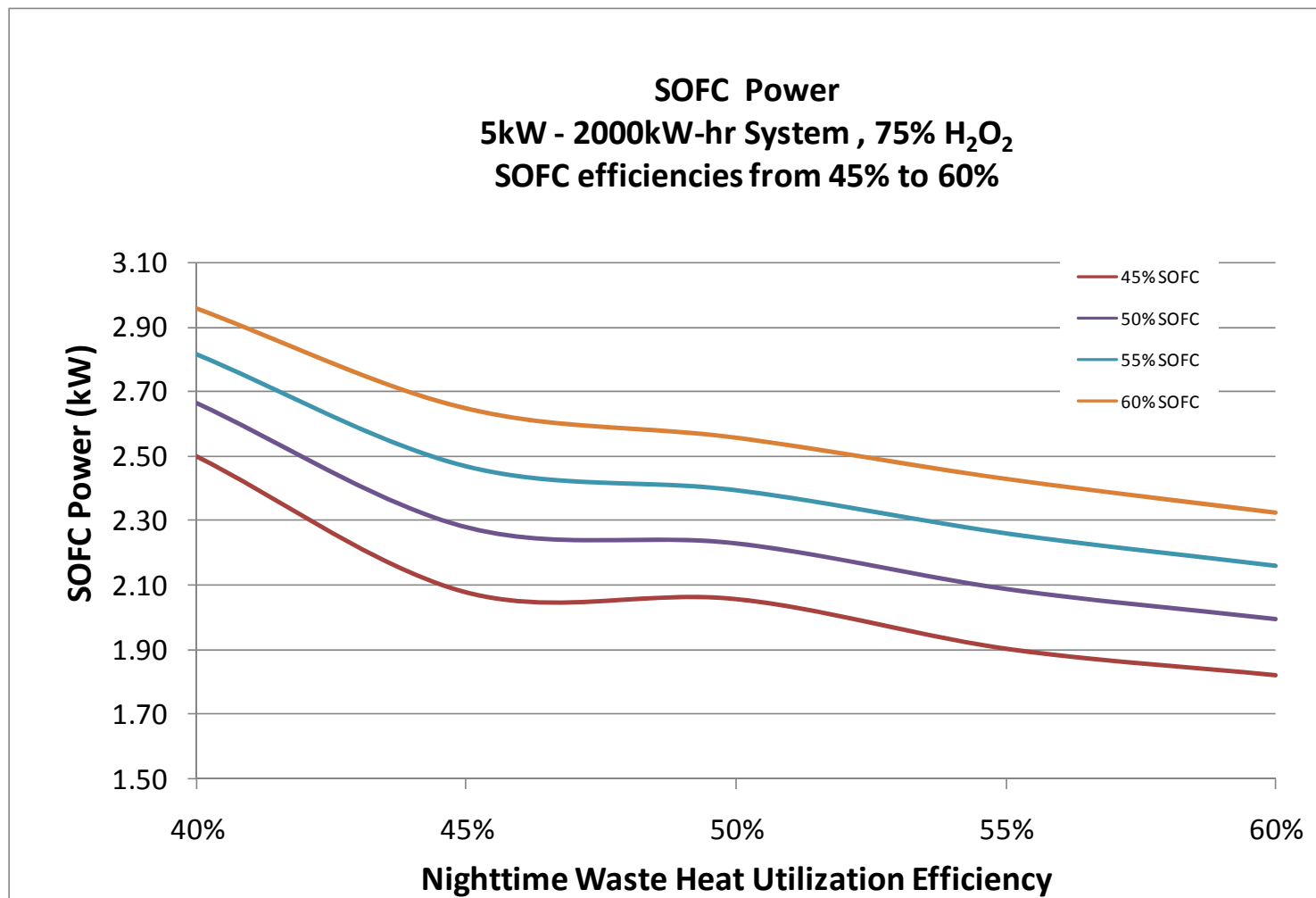
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Daytime Waste Heat vs. Waste Heat Utilization Efficiency
5kW - 2000kW-hr System with ORC with $\eta=20\%$, 55% H_2O_2
Day = Night, SOFC efficiencies from 45% to 60%

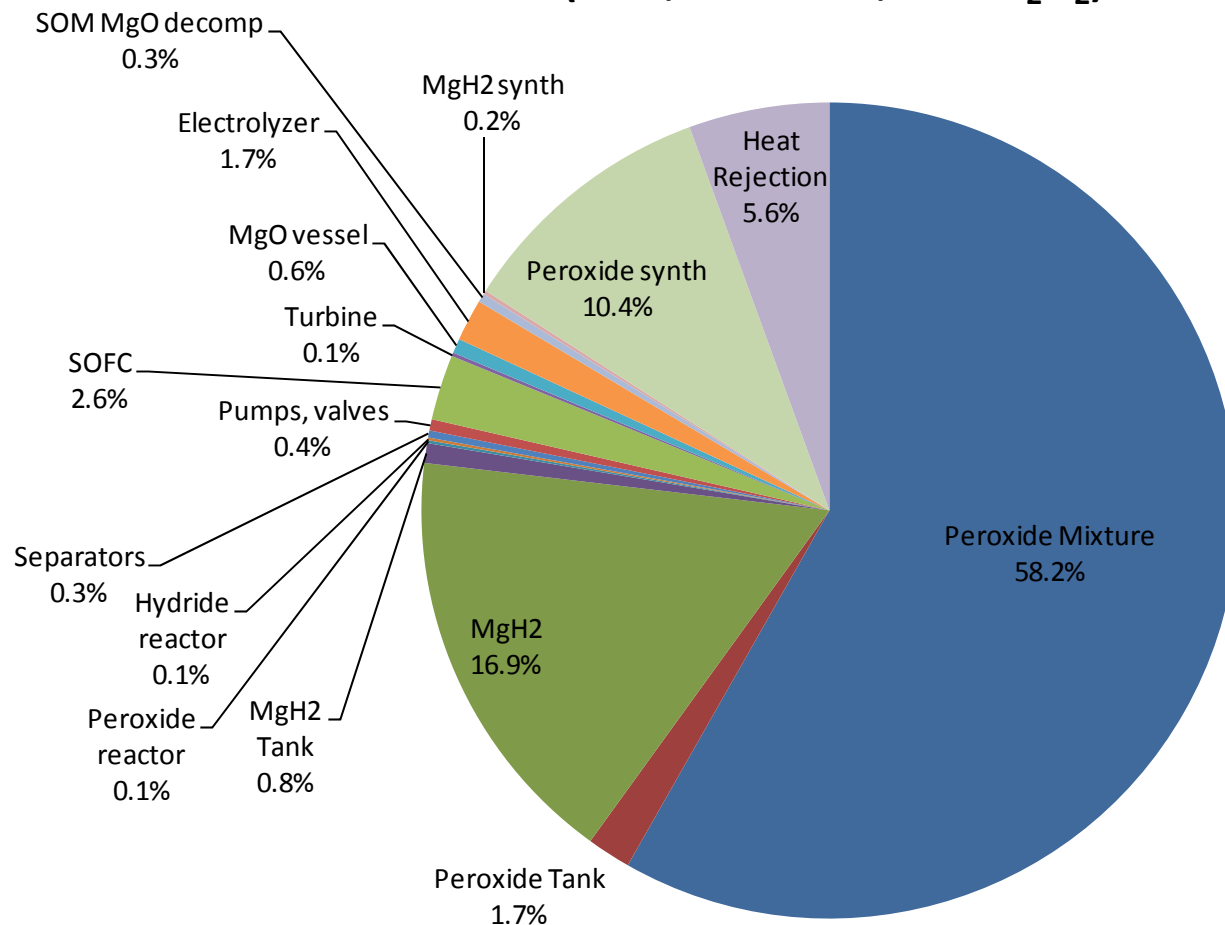


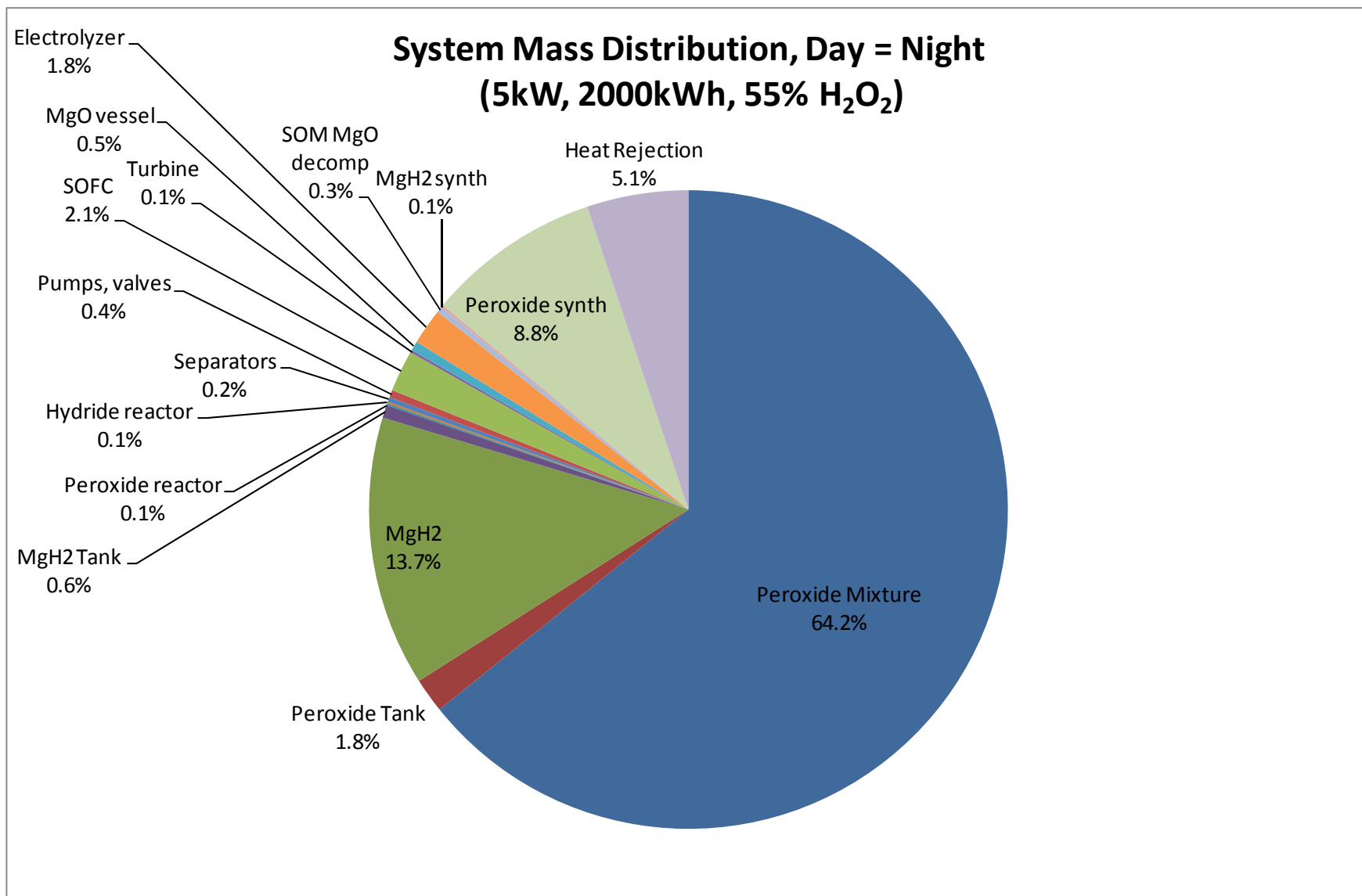
Daytime Waste Heat vs. Waste Heat Utilization Efficiency
2.0kW - 800kW-hr System with ORC with $\eta=20\%$, 55% H_2O_2
Day = Night, SOFC efficiencies from 45% to 60%



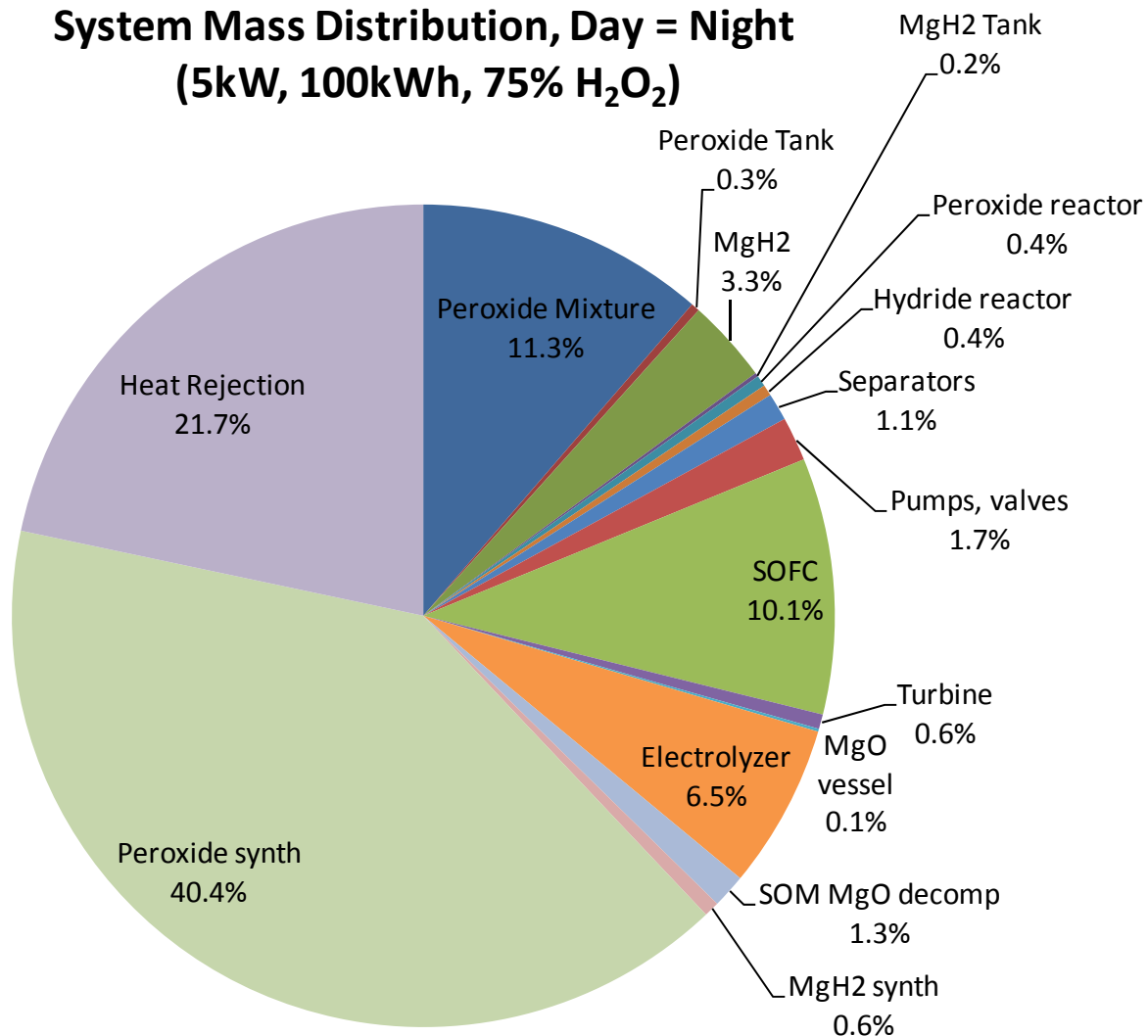


System Mass Distribution, Day = Night (5kW, 2000kWh, 75% H₂O₂)

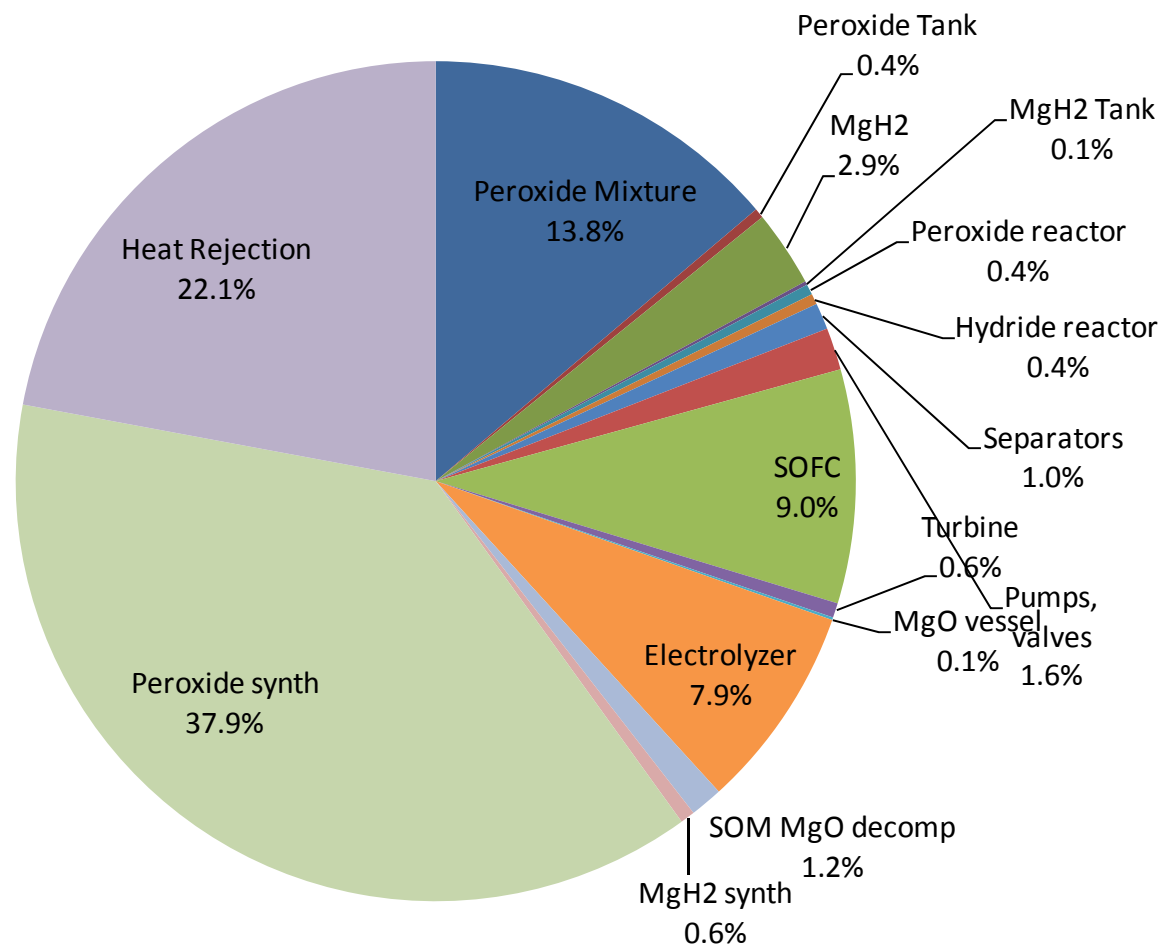


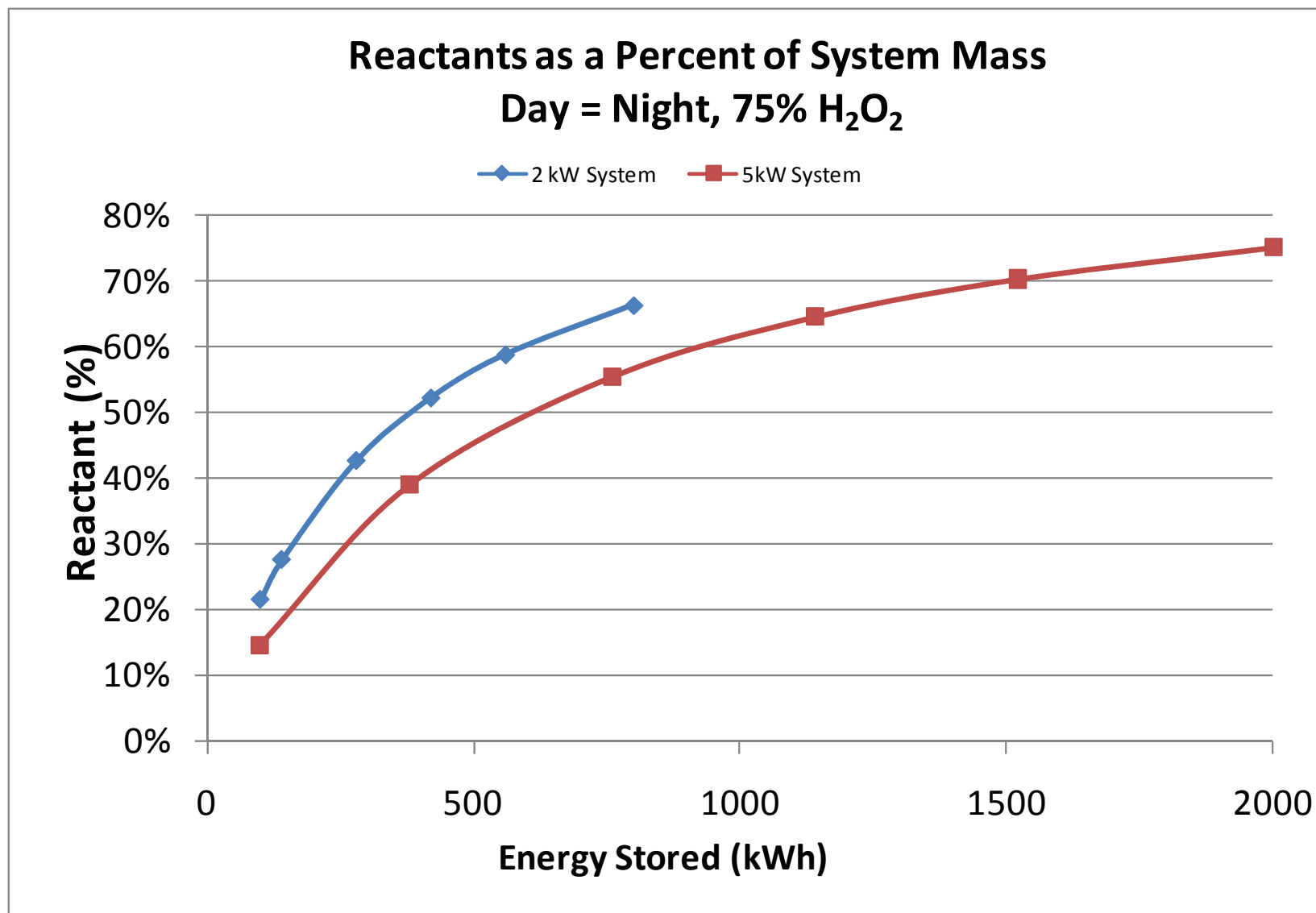


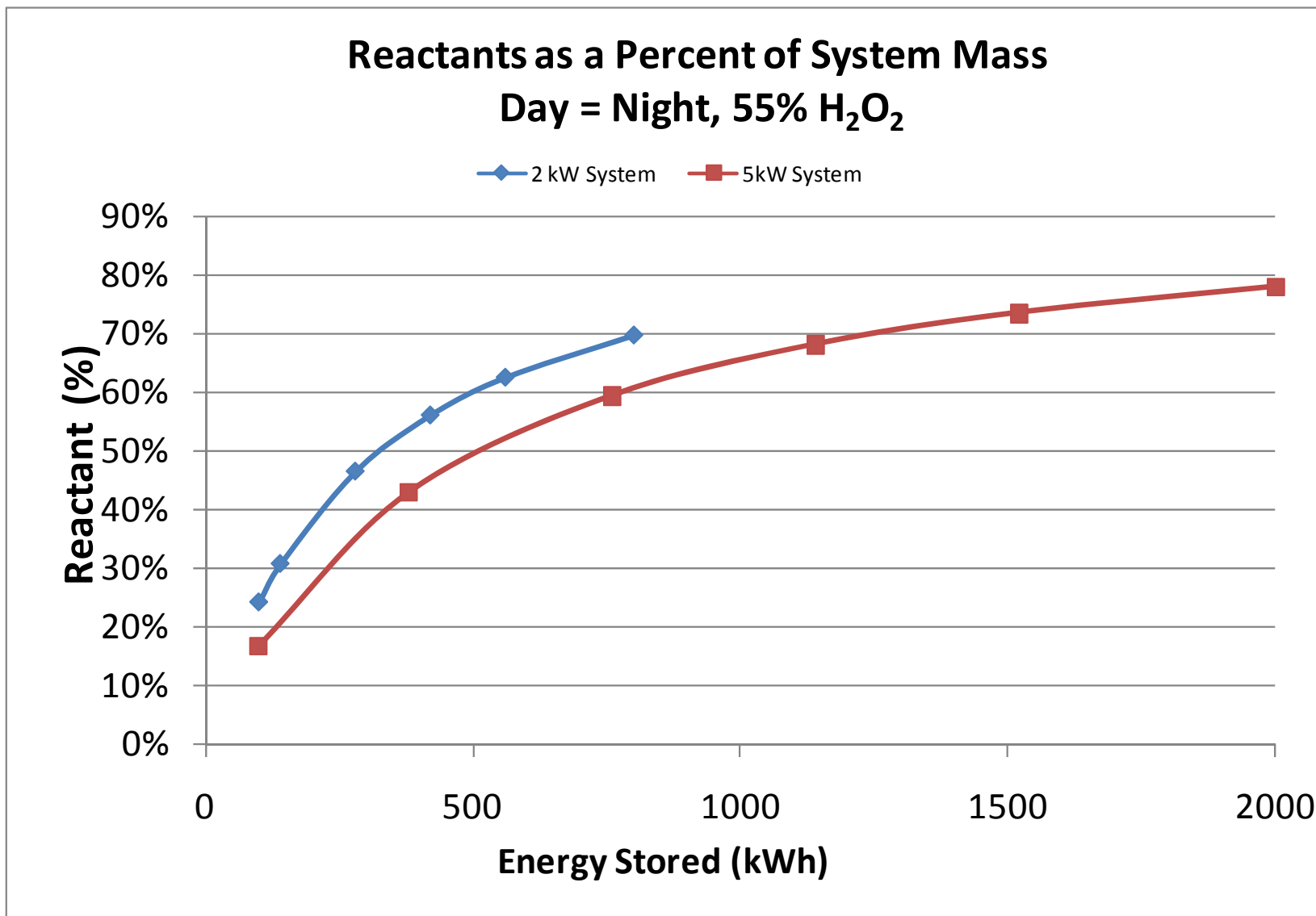
System Mass Distribution, Day = Night (5kW, 100kWh, 75% H₂O₂)



System Mass Distribution, Day = Night (5kW, 100kWh, 55% H₂O₂)







- **System is characterized by high energy density**
 - ~1.1 kWh.kg for complete TRESS
 - ~1.4 kWh/kg for power generation only
- **As expected, high concentrations of peroxide are favorable**
 - Less water to store and regenerate in peroxide mixture
- **Reactant storage is key mass and volume driver**
 - Efficiency is key for power gen components – mass is secondary (or lower)

TRESS Relevance to Lunar Exploration Objectives



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Category	Objective ID Number	Name	TRESS Technology Contribution
Life Support & Habitat	mLSH2	Develop and deploy closed loop life support systems to increase self sufficiency of future long duration human exploration missions and minimize the impact of humans on the environment.	TRESS technology of MgH ₂ and H ₂ O ₂ generation from regolith and water should enable lunar base life support system for long-duration human exploration missions. Being recyclable these materials need only solar power for their reproduction in the originally available quantities minimizing regolith mining requirements and environmental impact. TRESS energy generation system may become a universal modular solution for lunar base energy and life support.
General Infrastructure	mGINF1	Emplace support services on the Moon, including emergency response, to enable increased lunar activities.	As a result of "no-maintenance" storability of MgH ₂ and H ₂ O ₂ and potential for delivery of capsules with these energetic materials and their universal use in energy generation/life support systems - emergency response may be provided even in remote locations during lunar expeditions.
	mGINF3	Deploy a Moon-based infrastructure that can service space-based assets to reduce the cost and increase the lifetime of space system operations.	With development of MgH ₂ /H ₂ O ₂ propulsion systems (e.g. "Cold" solid rocket boosters) the lunar base may enhance its support for servicing of Moon orbiting and Earth/Moon space systems.
Operations, Testing & Verification	mOPS3	Establish crew-centered, real-time mission planning and control to enable self-sufficiency of lunar operations.	Because energetic materials in discussion may be generated in necessary quantities using regolith, water and solar energy then lunar base crew may plan activities and expeditions with less reliance to Earth-based resources and controls.
Power	mPWRI	Develop lunar power generation, storage, and distribution systems to satisfy the energy demands of lunar operations.	This is primary application for the TRESS system. We see this system as complimentary to RFC power units. Advantages of the TRESS energy storage and generation solution is in low-maintenance storage of the energetic materials that should be beneficial for long-term out-of-grid, shadowed locations.
Transportation	mTRANS3	Develop cryogenic fluid management, storage, and distribution systems to extend the lifetime and reduce the launch mass of exploration systems.	If TRESS energetic materials would have been produced and available in large quantities for use for long-term energy generation, intra-lunar transportation including hoppers and rovers, emergency deliveries, and, potentially, propulsion - then requirements for cryogenic storage and distribution systems may be significantly reduced and simplified.

TRESS Relevance to Lunar Exploration Objectives



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Category	Objective ID Number	Name	TRESS Technology Contribution
Surface Mobility	mSM1	Provide surface mobility capabilities to move crew outside the local area of a lunar outpost.	TRESS-based infrastructure and energy generation units should provide a compact/high power propulsion systems for moon rovers and other lunar outpost vehicles. Encapsulated materials can be easily delivered to remote locations. Hydrogen peroxide alone is a perfect life-support material suitable for emergency needs providing energy, water, and oxygen.
	mSM2	Provide surface mobility capabilities to move cargo and equipment outside the local area of a lunar outpost.	See above.
	mSM3	Provide surface mobility capabilities for local operations within a lunar outpost complex.	See above
Lunar Resource Utilization	mLRU3	Develop and validate tools, technologies and systems that extract lunar resources, to enable lunar resource utilization.	Recycling technologies and equipment, being essential parts of the TRESS technology, should provide a compact and high efficiency units for processing of lunar extracted materials (regolith and water). SOM process is suitable for separation of oxygen and metals from a variety of oxides that are available on the Moon.
	mLRU4	Develop and validate tools, technologies and systems that process lunar resources, to enable lunar resource utilization.	TRESS technology is an example of development and validation of tools, software, components and systems that perform various engineering processing of extracted lunar resources. TRESS processes and technologies being implemented, reduce the mass of materials and products that must be launched from Earth for activities on the Moon and other destinations.
	mLRU6	Develop, validate, and incorporate new products and associated technologies and systems that effectively utilize lunar resources and products, to support further lunar resource utilization.	See above. "Cold" solid rocket boosters that potentially may be fabricated on the Moon with TRESS energetic materials may enhance launch capabilities from the Moon base that are essential for the Mars program.
	mLRU7	Produce propellants and life support and other consumables from lunar resources, to improve the productivity of lunar operations.	TRESS concept, technologies, and equipment, being implemented, should ensure energy independence and life support to the whole cycle of lunar base operations and generation of a significant stock of energetic materials for variety of applications (see above).

TRESS Relevance to Lunar Exploration Objectives



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Category	Objective ID Number	Name	TRESS Technology Contribution
	mLRU8	Construct facilities and manufacture hardware, materials, and other infrastructure growth products and capabilities from lunar resources, to improve the productivity of lunar operations.	See above.
	mLRU9	Repair, fabricate and assemble parts and products using extracted and processed in-situ resources to support self-sustained, long duration missions.	See above.
	mLRU10	Produce products from lunar resources that can be used for missions to other destinations, to enable and support future exploration.	See above.

- High temperature chemical processes
 - High efficiency thermal energy conversion
 - High efficiency heat rejection
 - Self-sustained, stable operational environment
- High volumetric and gravimetric energy density
 - High efficiency storage of H_2 and O_2
 - Scaling-up storage (duration) increases overall system energy density
- Low material flow rates
 - Simplifies material supply subsystem components
 - Compact energy generation modules
- No maintenance required for materials stored for extended time periods
 - Opportunity to generate and store materials in-advance for later use
 - Materials are safe and easily transportable
- Efficient material recycling technologies
 - System based on tested processes – need to develop lunar-specific designs
 - Experimental data are available to support system performance estimates
- Recycling process synergy with ISRU
 - SOM process may be used for production of a variety of metals and for generation of oxygen from regolith
 - Synthesized hydrogen peroxide may be used as a compact water/oxygen long-term storage.

- Compact size
 - The system can be delivered in one module to the Moon ready for operations after integration with solar array energy source
 - Most components (e.g. turbine/SOFC/H₂O₂ reactor/ powder supply system) are small
 - The unit is easily transportable to other lunar locations
- Encapsulated fueling options
 - Provide opportunity to fuel mobile/remote units
 - May be easily transported via hoppers to any lunar location
 - Standardized recycling interface, centralized recycling facility

TRESS Technology Applications/Variations and Program Plan

- **MgH₂ + O₂ system (instead of H₂O₂)**
 - **Eliminates most complex synthesis process (and contaminants)**
- **Interplanetary Lunar Network (ILN)**
 - **<100W systems for remote applications**
- **Emergency oxygen, water or heat delivery**
- **Rocket propulsion using ISRU + TRESS derived propellants**
 - **MgH₂ + H₂O₂ rocket has Isp > 300 sec**
- **Terrestrial vehicle applications – compact H₂ for fuel cells**
- **Underwater Applications (or other sealed environments)**

- **ATK and ACEnT Laboratories propose a phased program for the development of a TRESS system with a TRL of 6 by 2017-2018. The program is divided into 3 phases as follows:**
 - Phase I: Electrical Energy Generating Module Demo and TRESS System Analysis
 - Phase II: TRESS Small Scale Prototype Demo Fabrication and Testing, and
 - Phase III: Full-scale TRESS Prototype Development, Design, and Testing.
- **Each phase will lead to concrete deliverables and will follow a detailed project work plan to support efficient resource planning and program management**
- **Detailed schedules have been developed for each of the program phases using MS Project software**
- **All this work would be expected to be conducted in close cooperation with NASA Glenn RC and NASA Johnson SC.**

- **A comprehensive evaluation of energy cycles for particular requirements and assumptions (total energy stored, aqueous peroxide concentration, scenario of the system delivery, installation and use, etc.)**
- **Analysis of system architecture including portable, stationary, and mobile versions; modular design engineering solutions; operational scenarios; infrastructure requirements; quantitative estimates of impact of TRESS introduction and use to lunar base infrastructure requirements**
- **Detailed design of a representative small-scale MgH_2 powder/steam reactor with a powder delivery system and a MgO collection system**
- **Selection of an electrical power generating system (SOFC/Turbine/Stirling) suitable for small-scale application (200W total).**
- **Selection, procurement, and assembly of a 55% aqueous hydrogen peroxide decomposition reactor**
- **Power generation system assembly and comprehensive testing of all its components to obtain data justifying TRESS performance estimates, lifecycle (essential features from short duration tests), and material delivery and dispensing.**
- **Detailed analysis of recycling technologies including bench-scale testing of key recycling processes to collect data for TRESS closed-loop material and energy cycle and for detailed design of the prototype recycling modules**
- **Analysis of safety factors will be performed, project risk will be quantified on the subsystems and systems level**
- **Resourced Phase II project plan will be developed and presented to the customer for approval.**

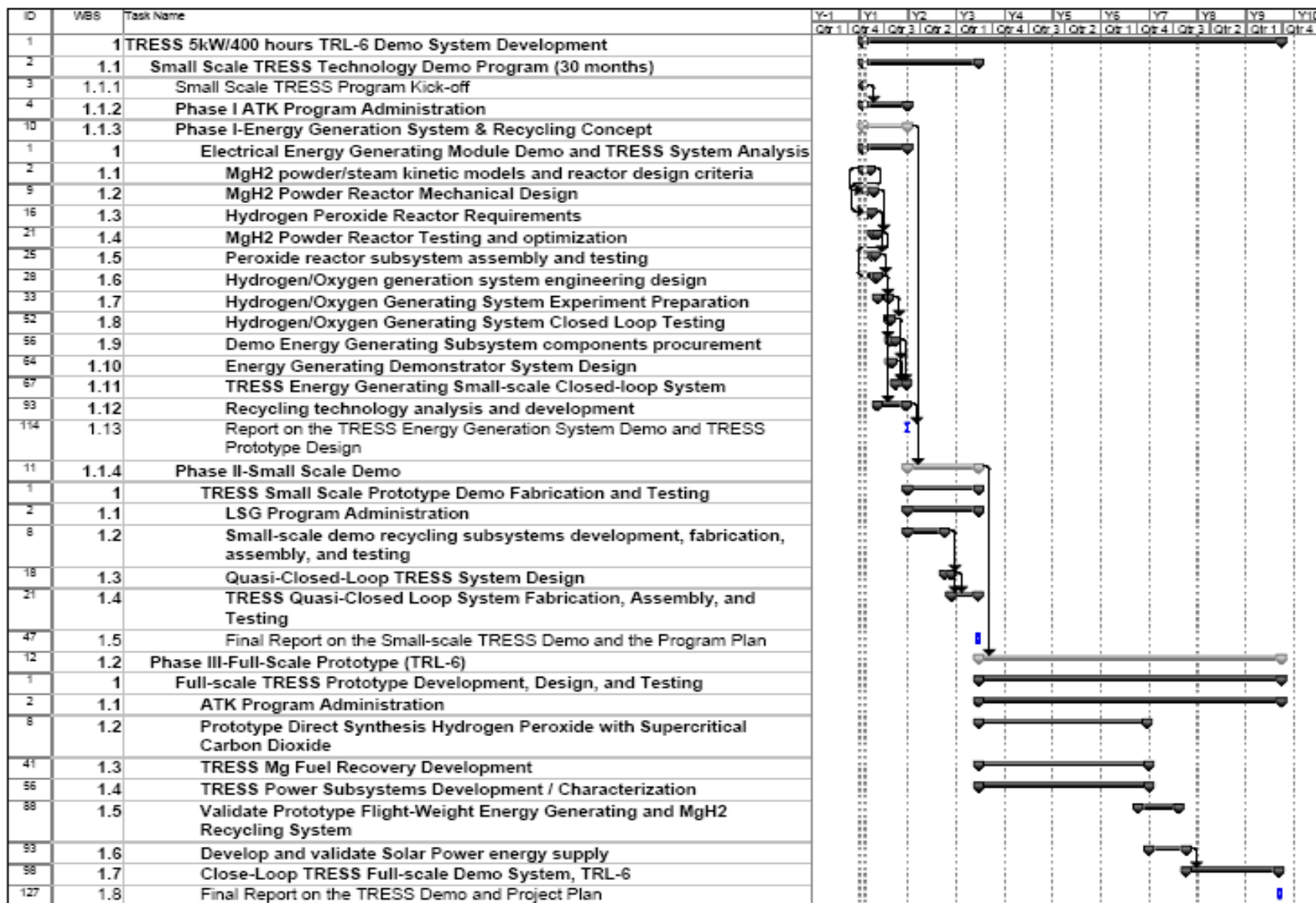
- **Assemble a quasi-closed-loop small-scale TRESS unit that should allow us to run a number of energy generating/materials recycling cycles**
- **Collect all the necessary data for transition to detailed design and implementation of a Phase III program to obtain a TRL-6, full-scale, TRESS unit with given requirements**
- **Provide NASA with a comprehensive program plan with particular technology development subprograms, a risk management system and budget**
- **The Phase II includes ~8 months of total testing time of the system and its components. Because TRESS energetic materials (MgH_2 and H_2O_2) and recycling technologies development require significant effort and time for all the processes being tested and optimized, we plan to simulate TRESS recycling processes using already available hardware, upgraded and customized for TRESS the application.**

- **This phase is scheduled for a period of ~7 years and will result in the development of a TRESS system prototype with all of the relevant technologies, components, and system comprehensively tested in a terrestrial and a simulated lunar environment (where practical).**

TRESS Technology Development Master Plan



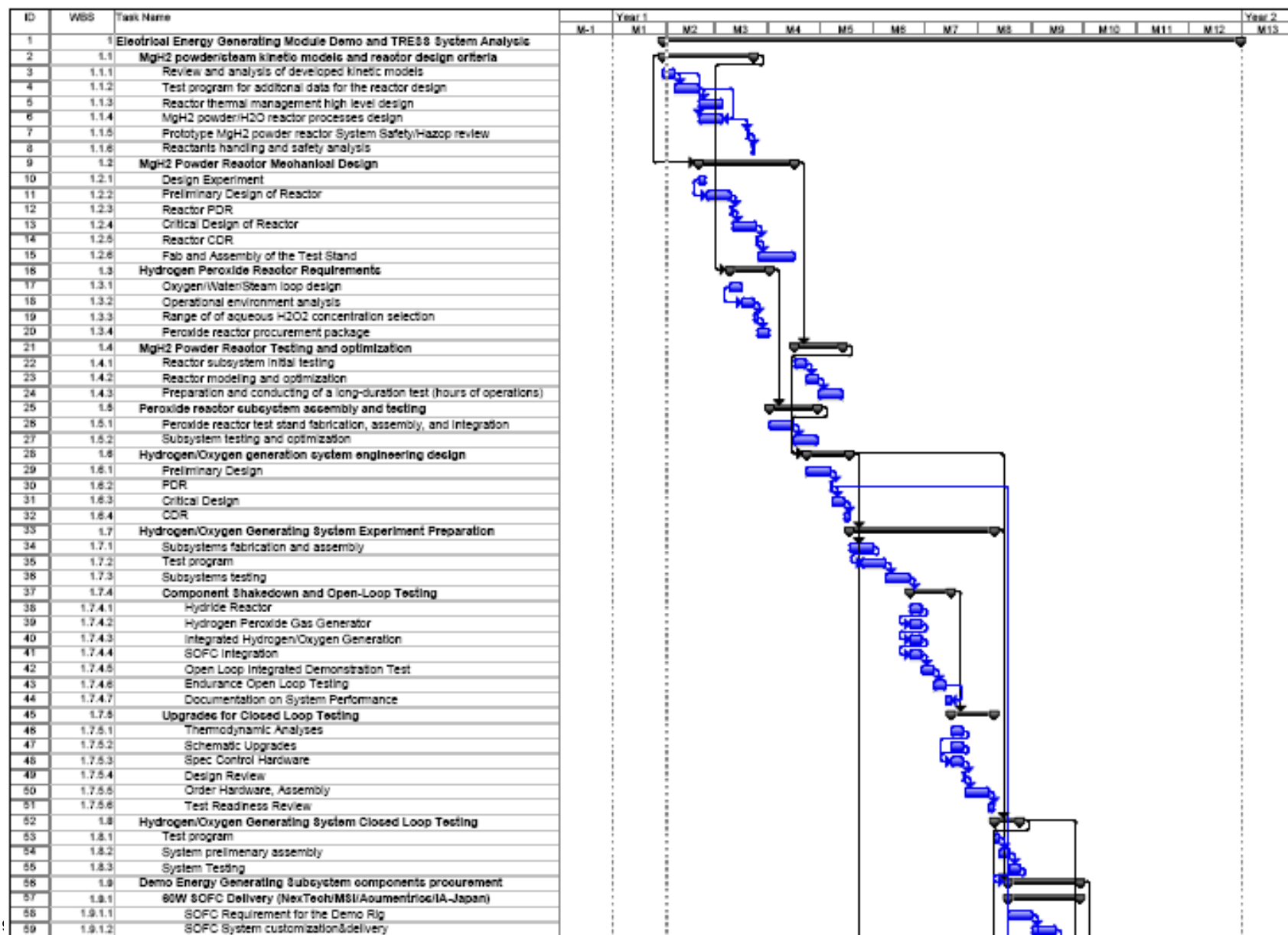
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TRESS Technology Development Phase I-A



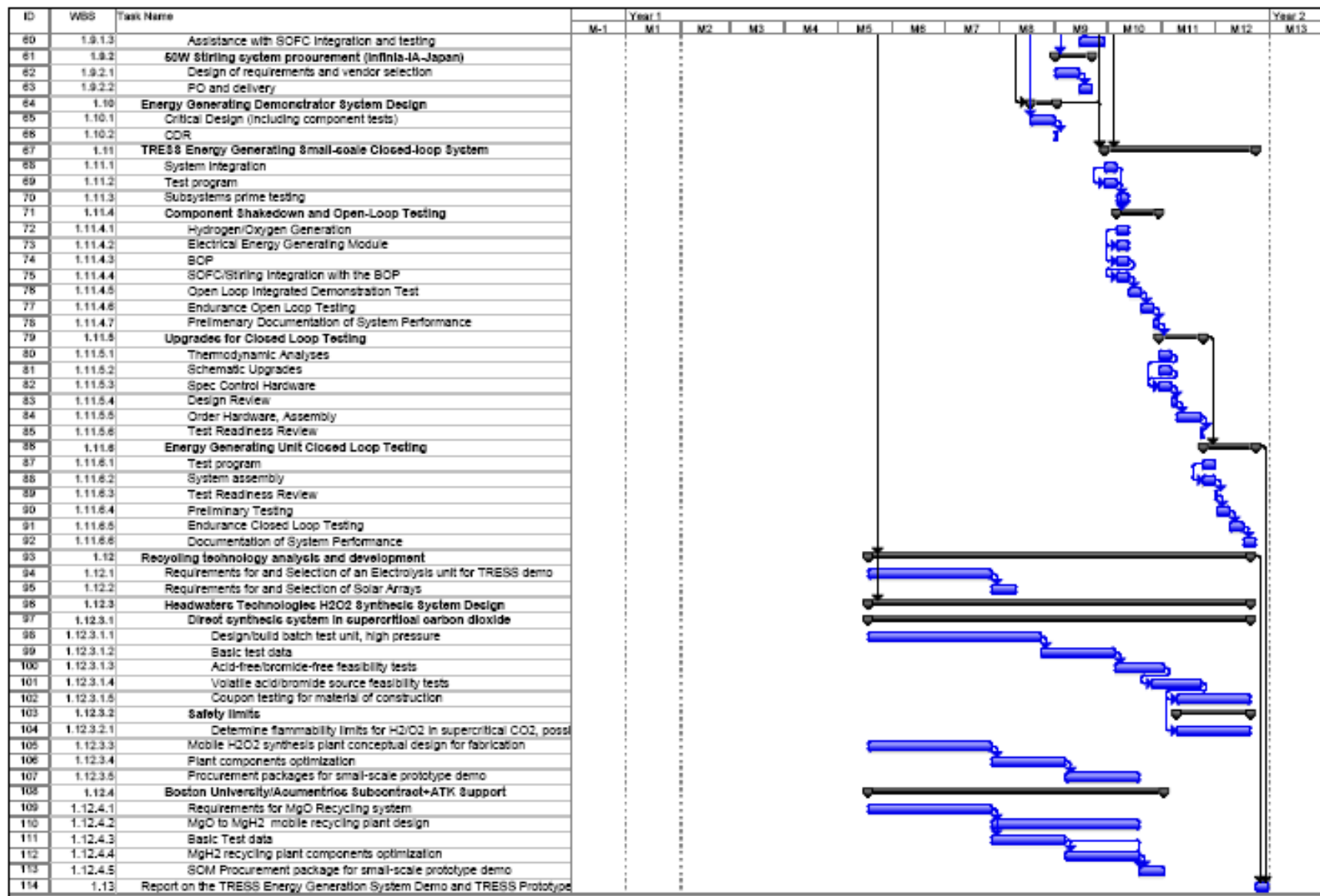
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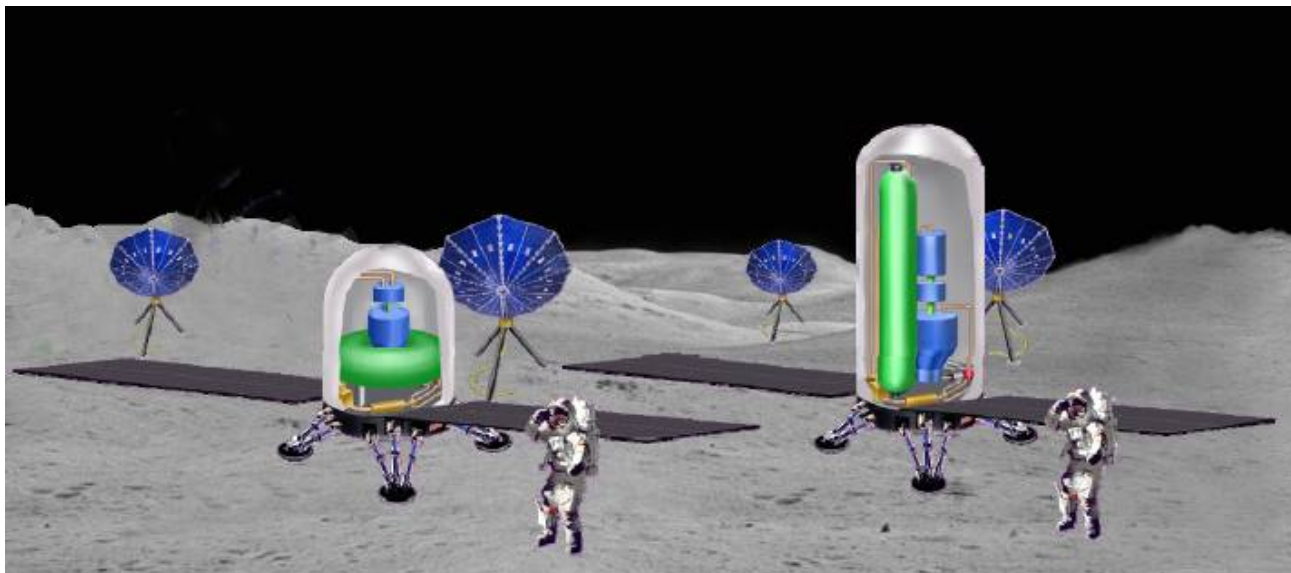
TRESS Technology Development Phase I-B



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- Our Thermochemical Regenerative Energy Storage System (TRESS) is a promising candidate to meet NASA's requirements in a highly compact, efficient package
- The system performance and form factor is superior to batteries and $H_2 - O_2$ regenerative fuel cell based systems
- TRESS is highly compatible with future in-situ resource utilization (ISRU) for added long-term benefits
- ATK has committed significant funding to the underlying CHOSS system development





Thank You!